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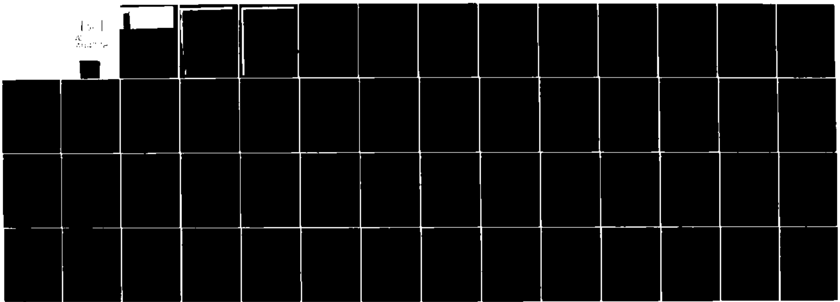

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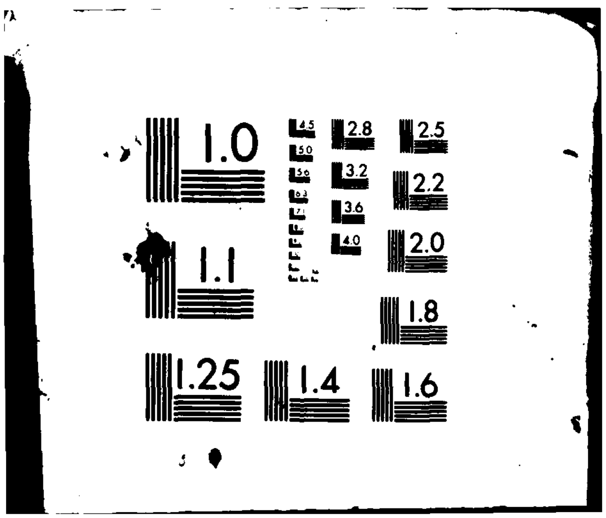
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INTERACTION OF OBLIQUE SHOCK AND DETONATION WAVES

by

Y. SHENG and J. P. SISLIAN

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The interaction of an oblique shock wave and an oblique detonation wave which deflect the flow in the same direction is analyzed. The detonation wave is assumed to be an exothermic gasdynamic discontinuity. A criterion is developed and used to determine whether or not a theoretical solution of the problem describes a physically realizable interaction configuration. It is found that the reflected wave is, in general, a rarefaction wave. Only for very low values of the heat release parameter of the detonation wave the reflected

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wave has been found to be a shock wave. Domains of existence of such resulting wave interaction configurations are established for different values of the oncoming Mach number, $6 \leq M \leq 8$, the heat release parameter, $3 \leq Q \leq 8$, and the specific heat ratios for the combustion products behind the detonation wave, $1.30 \leq \gamma \leq 1.33$. It is also found that double discontinuity configurations, representing the refraction of a detonation wave at a combustible/non-combustible interface (a limiting case of the considered interaction problem) can exist for certain values of the flow parameters involved and for different specific heat ratios of the gases in front of and behind the detonation wave. The magnitudes of the heat release parameter and specific heat ratio of the combustion products affect significantly the interaction pattern of shock and detonation waves. It is, therefore, concluded that the interaction problem considered be based on a detailed thermo-chemical analysis for given combustible mixtures of gases.

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Abstract

The interaction of an oblique shock wave and an oblique detonation wave which deflect the flow in the same direction is analyzed. The detonation wave is assumed to be an exothermic gasdynamic discontinuity. A criterion is developed and used to determine whether or not a theoretical solution of the problem describes a physically realizable interaction configuration. It is found that the reflected wave is, in general, a rarefaction wave. Only for very low values of the heat release parameter of the detonation wave the reflected wave has been found to be a shock wave. Domains of existence of such resulting wave interaction configurations are established for different values of the oncoming Mach number, $6 \leq M \leq 8$, the heat release parameter, $3 \leq Q \leq 8$, and the specific heat ratios for the combustion products behind the detonation wave, $1.30 \leq \gamma \leq 1.33$. It is also found that double discontinuity configurations, representing the refraction of a detonation wave at a combustible/noncombustible interface (a limiting case of the considered interaction problem) can exist for certain values of the flow parameters involved and for different specific heat ratios of the gases in front of and behind the detonation wave. The magnitudes of the heat release parameter and specific heat ratio of the combustion products affect significantly the interaction pattern of shock and detonation waves. It is, therefore, concluded that the interaction problem considered be based on a detailed thermo-chemical analysis for given combustible mixtures of gases.

Contents

Notation

Symbols

a	sound speed
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
M	Mach number
M_n	normal Mach number
$P_{ij} = p_i/p_j$	pressure ratio
q_{ij}	heat release in the wave separating flow regions i and j
$Q_{ij} = q_{ij}/c_{p_j}T_j$	heat release parameter
R	gas constant
T	absolute temperature
u	component of flow velocity normal to discontinuity surface
v	component of flow velocity tangential to discontinuity surface
V	*flow velocity*
ρ	density
γ	specific heat ratio
δ	flow deflection angle through a wave

Subscripts

i	downstream of a wave
j	upstream of a wave
CJ	Chapman-Jouguet condition
ℓ	lower limit
u	upper limit

Superscripts

o	stagnation values of the corresponding flow variables

1. INTRODUCTION

The use of oblique detonation waves in ramjets that operate at hypersonic speeds have recently received considerable attention (Refs. 1, 2). A flow device utilizing this mode of combustion, as opposed to the supersonic diffusive burning mode, offers several advantages (see, for example, Ref. 3). Proposed diffuser-combustor model flow configurations involving plane oblique detonation waves (Refs. 1, 2, 4) entail, by necessity, the interaction of such combustion waves with the oblique shock waves formed on the forebody at high supersonic flight speeds. In view of such possible applications, the shock wave and detonation wave interaction problem depicted in Fig. 1 is investigated in the present Note. Fuel is injected along the wall AB of the inlet into the supersonic stream and is assumed fully mixed with the air at station B. A detonation wave across BO stabilized by means of a second wedge interacts with the oblique shock wave AO formed by the forebody. Of primary interest are the nature and magnitude of the resulting possible wave configurations, as well as their domains of existence as functions of the oncoming flow Mach number, the strengths of the shock and detonation waves, the amount of heat released by the burning reaction per unit mass of gas, and the specific heat ratios of the combustion product behind the detonation wave.

It is easy to visualize that in order to equilibrate the pressures in the airstreams on both sides of the intersection point O, the transmitted discontinuity must be a shock wave, OE; a contact discontinuity, OC, must then separate the airstreams of different entropies passing through the two different sets of discontinuities. However, such a "triple discontinuity" configuration where only a reflected Mach wave exists represents a special limiting case of the more general resulting flow pattern when a reflected shock or rarefaction wave is present between the detonation wave OB and the contact surface OC. Figures 1(b) and 1(c) represent the resulting discontinuity patterns when the reflected wave is a rarefaction wave and a shock wave, respectively. It can be easily shown that there can be no other discontinuities in the interaction flow pattern, i.e., no discontinuity other than the reflected rarefaction or shock wave can exist between the detonation wave and the contact surface; also, no other discontinuity can exist between the transmitted shock wave, OE, and the contact surface, OC (see Ref. 5, Ch. 11).

A Chapman-Jouguet detonation wave is adopted in the present Note. According to this model the detonation wave consists of a shock wave in which chemical reactions occur instantaneously, i.e., the detonation wave is considered as an exothermic gasdynamic discontinuity. Although for most fuels utilized in ramjets the temperature behind the detonation wave would be too high to consider the flowing medium as a perfect gas, in the present Note real-gas effects are neglected for the sake of simplicity. The effects of chemical reactions, as well as of the various fuel/air mixture ratios are accounted for by different constant specific heat ratios before and after the detonation wave, and by different values of the heat release parameter.

The shock and detonation wave interaction was also investigated by Rues (Ref. 6) for the particular case when the resulting wave configuration contains only a reflected Mach wave; no allowance was made f r the change of specific heat ratios across the detonation wav A qu cative analysis of a limiting case of the interaction problem, i.e. t e fraction of a detonation wave at a combustible/non-combustible gas interface, is given in Ref. 7.

2. OBLIQUE DETONATION WAVE RELATIONS

Figure 2 is a sketch of the two-dimensional flow through a plane oblique detonation wave. The laws of conservation of mass, momentum and energy applied to the plane oblique exothermic discontinuity considered yielu the following relationships:

Continuity:

$$\rho_j u_j = \rho_i u_i \tag{1}$$

Momentum:

$$p_j + \rho_j u_j^2 = p_i + \rho_i u_i^2 \tag{2}$$

and

$$v_j = v_i \tag{3}$$

Energy:

$$\frac{u_j^2+v_j^2}{2} + \frac{a_j^2}{\gamma_j-1} + q_{ij} = \frac{u_i^2+v_i^2}{2} + \frac{a_i^2}{\gamma_i-1} \tag{4}$$

The premixed gaseous mixture of reactants, and the gaseous reaction products are assumed to be perfect gases with equations of state of the form

$$p_k = \rho_k R_k T_k \tag{5}$$

Manipulation of the above equations yields the following relationships for the determination of the flow variables behind the detonation wave in functions of the pressure ratio $P_{ij} = p_i/p_j$:

Normal velocity ratio (or density ratio):

$$\frac{\rho_j}{\rho_i} = \frac{u_i}{u_j} = \frac{P_{ij}+b_j+\bar{Q}}{b_i P_{ij}+1}; \qquad \bar{Q}_{ij} = \frac{2\gamma_j}{(\gamma_j-1)} Q_{ij}; \qquad Q_{ij} = \frac{q_{ij}}{c_{p_j} T_j}; \qquad b_k = \frac{\gamma_k+1}{\gamma_k-1} \tag{6}$$

Temperature ratio:

$$\frac{T_i}{T_j} = \frac{R_j}{R_i} P_{ij} \frac{P_{ij}+b_j+\bar{Q}_{ij}}{b_i P_{ij}+1} \tag{7}$$

Mach number ratio:

$$\frac{M_i}{M_j} = \sqrt{\frac{\gamma_j}{\gamma_i}\frac{1}{P_{ij}} \frac{1 - \frac{P_{ij}-1}{\gamma_j M_j^2}\left(2 - \frac{P_{ij}-1}{\gamma_j M_{jn}^2}\right)}{1 - \frac{P_{ij}-1}{\gamma_j M_{jn}^2}}} \tag{8}$$

where the normal component of the Mach number of the flow before the detonation wave, M_{jn}, is given by

$$M_{jn}^2 = \frac{(P_{ij}-1)(b_i P_{ij}+1)}{\gamma_j \left(\frac{2}{\gamma_i - 1} P_{ij} - \frac{2}{\gamma_j - 1} - \bar{Q}_{ij} \right)} \tag{9}$$

Normal Mach number ratio:

$$\frac{M_{in}}{M_{jn}} = \sqrt{\frac{\gamma_j}{\gamma_i} \frac{1}{P_{ij}} \frac{P_{ij}+b_j+\bar{Q}_{ij}}{b_i P_{ij}+1}} \tag{10}$$

Total pressure ratio:

$$\frac{p_i^o}{p_j^o} = P_{ij} \frac{\left[1 + \frac{\gamma_i - 1}{2} M_j^2 \left(\frac{M_i}{M_j} \right)^2 \right]^{\gamma_i/\gamma_i - 1}}{\left(1 + \frac{\gamma_j - 1}{2} M_j^2 \right)^{\gamma_j/\gamma_j - 1}} \tag{11}$$

Total temperature ratio:

$$\frac{T_i^o}{T_j^o} = \frac{\gamma_j(\gamma_i - 1)}{\gamma_i(\gamma_j - 1)} \frac{R_j}{R_i} \left[1 + \frac{Q_{ij}}{\left(1 + \frac{\gamma_j - 1}{2} M_j^2 \right)} \right] \tag{12}$$

For strong detonations considered here, the ratio $P_{ji} = p_j/p_i$ will vary in the interval

$$0 < P_{ji} < P_{jiCJ} \tag{13}$$

where $P_{jiCJ} = 1/P_{ijCJ}$ can be determined from Eqs. (9) and (10) with $M_{in} = 1$. We get

$$P_{ijCJ} = \frac{\frac{\gamma_i+1}{\gamma_j-1} \left(1 + \frac{\gamma_j - 1}{2} \bar{Q}_{ij} \right) + \sqrt{\left[\frac{\gamma_i+1}{\gamma_j-1} \left(1 + \frac{\gamma_j - 1}{2} \bar{Q}_{ij} \right) \right]^2 - b_i(b_j+\bar{Q}_{ij})}}{b_i} \tag{14}$$

The flow deflection angle is given by

$$\delta_{ij}' = \pm \tan^{-1} \left\{ \frac{P_{ij}-1}{[\gamma_j M_j^2 - (P_{ij}-1)]} \sqrt{\frac{\gamma_j M_j^2 [(b_i - 1)P_{ij} - (b_j - 1) - \bar{Q}_{ij}]}{(P_{ij}-1)(b_i P_{ij}+1)} - 1} \right\} \tag{15}$$

where the upper sign corresponds to a clockwise deflection. When $\gamma_i = \gamma_j$ and $q_{ij} = 0$, the above equations reduce to the usual oblique shock wave relations. Equation (15) is plotted on Figs. 3-5 for various values of Q_{ij}, γ_i and M_j.

BASIC EQUATIONS AND SOLUTION OF THE INTERACTION PROBLEM

The three possible interaction configurations are depicted in Fig. 1. regions (1)-(5) divided by the waves the flow is uniform. In terms of pressure ratio P_{ij} and the flow deflection angle δ_{ij} across the wave arating region i after the wave from region j before it, we can write following conditions:

$$P_{51} = P_{43}P_{32}P_{21}$$

$$\log P_{51} = \log P_{43} + \log P_{32} + \log P_{21} \tag{16}$$

d

$$\delta_{51} = \delta_{21} + \delta_{32} + \delta_{43} \tag{17}$$

lid across the contact discontinuity OC. The deflection angles in . (17) are given by Eq. (15) with the appropriate values of γ_j, Q_{ij}, and P_{ij} on the corresponding discontinuity (in the case of a shock scontinuity, the relevant value of γ is assumed conserved across the ock wave and $Q_{ij} = 0$). In the case of a reflected rarefaction wave, e corresponding deflection angle is given by

$$\delta_{43} = b_3 \tan^{-1}\sqrt{\frac{M_4^2-1}{b_3}} - \tan^{-1}\sqrt{M_4^2-1} -$$

$$- b_3 \tan^{-1}\sqrt{\frac{M_3^2-1}{b_3}} + \tan^{-1}\sqrt{M_3^2-1} \tag{18}$$

ere

$$M_4 = \sqrt{\frac{2}{\gamma_3-1}\left[\frac{1+\frac{\gamma_3-1}{2}M_3^2}{P_{43}^{\gamma_3-1/\gamma_3}} - 1\right]} \tag{19}$$

Elimination of P_{43} from Eqs. (16) and (17) yields the following uations for the single unknown P_{51}:

$$\delta_{21}(P_{21}, \gamma_1, M_1) + \delta_{32}[P_{32}, \gamma_2, \gamma_3, M_2(P_{21}, \gamma_1, M_1), \bar{Q}_{32}] \pm$$

$$\pm \delta_{43}\left[\frac{P_{51}}{P_{32}P_{21}}, \gamma_3, M_3(P_{32}, \gamma_2, \gamma_3, M_2(P_{21}, \gamma_1, M_1), \bar{Q}_{32})\right] -$$

$$- \delta_{51}(P_{51}, \gamma_1, M_1) = 0 \tag{20}$$

r given M_1, P_{21}, P_{32}, γ_1, γ_3 and Q_{32} (given fuel/air mixture), we can termine P_{51} from Eq. (20). Equations (6)-(15) and Eqs. (18) and (19) ll then yield the values of all the flow variables of interest in the nsidered interaction problem. In the case of vanishingly small reflected ve (triple discontinuity configuration) $P_{51} = P_{32}P_{21}$; Eq. (20) is then lved for P_{32} for given values of P_{21}.

A graphical illustration of the solution is presented on Fig. 6 for the case when $M_1 = 7$, $P_{21} = 2.6$ ($M_2 = 5.92$), $\gamma_3 = 1.3$ and $Q_{32} = 8$. Only the right-hand halves of the incident shock polar I and detonation polar II are considered in the present investigation, as it is assumed that the shock and detonation waves deflect the flow in the same direction. The intersection point A of the detonation polar II and the shock polar I would then represent the resulting interaction pattern with a reflected Mach wave [triple discontinuity configuration, case (a) in Fig. 1]. Hence, for values of $P_{32} > P_{32A}$, the value of P_{32} at point A, we would have reflected rarefaction wave configurations [case (b) in Fig. 1] determined by points B and B' of intersection of the corresponding epicycloid IV with the shock polar I, and for $P_{32} < P_{32A}$, either the reflected shock configuration [case (c) in Fig. 1] determined by point C of intersection of the shock polar III drawn from Point P_{32} and the shock polar I, or the reflected rarefaction wave configuration determined by point C' of intersection of the epicycloid IV drawn from point P_{32} and the shock polar I. For $P_{32} = P_{32A}$ a reflected rarefaction wave interaction configuration given by point A' of intersection of the epicycloid drawn from point P_{32A} and the shock polar I, is also possible. Thus for a given combination of P_{21} and P_{32}, it is possible to have two sets of solutions corresponding respectively to points A, B, C and A', B', C' in Fig. 6. It is obvious that not all the solutions are physically realizable. Whether a mathematical solution of Eq. (20) is physically realizable or not depends on the stability of the resulting triple discontinuity configuration to small perturbations.

4. STABILITY CRITERION FOR REFLECTED MACH WAVE CONFIGURATIONS

Let us superimpose a small pressure disturbance Δp on the flow regions (3), (4) and (5) [Fig. 1(a)] downstream of the discontinuities OB and OE. This small pressure disturbance will cause variations in the flow deflection angles across the reflected Mach wave and the transmitted shock wave OE, $\Delta\delta_R$ and $\Delta\delta_T$, respectively, and will not affect the flow in regions (1) and (2). If the rate of change of the flow deflection angle across the reflected Mach wave is less than the rate of change of the flow deflection angle across the transmitted shock wave, i.e., if

$$\left.\frac{d\delta}{dp}\right|_R \leq \left.\frac{d\delta}{dp}\right|_T \tag{21}$$

then the reflected Mach wave configuration is stable and, hence, physically realizable. Indeed, if $\Delta p > 0$, then from Eq. (21), $\Delta\delta_R < \Delta\delta_T$ and the streamlines crossing these waves will diverge and result in a pressure decrease which will restore the equilibrium state. If $\Delta p < 0$, then $\Delta\delta_R > \Delta\delta_T$, and the streamlines will converge and result in a pressure increase which will restore the equilibrium state. It is easy to see that if condition (21) is violated, the reflected Mach wave configuration becomes unstable and hence physically not realizable. Equation (21) can be written in a more convenient form

$$\left.\frac{d\delta}{d\ell np}\right|_R \leq \left.\frac{d\delta}{d\ell np}\right|_T \tag{22}$$

Substitution of the expressions for the derivatives in the above equation, derived in the Appendix, yields

$$\frac{P_{51}}{\dfrac{A(P_{51}-1)^2(P_{51}-P_{51_{max}})}{[\gamma_1 M_1^2-(P_{51}-1)]^2(AP_{51}+1)}-1}\left\{\frac{\gamma_1 M_1^2}{[\gamma_1 M_1^2-(P_{51}-1)]^2}\left[-\frac{A(P_{51}-P_{51_{max}})}{(AP_{51}+1)}\right]^{1/2} - \frac{A[(AP_{51}+1)(2P_{51}-1-P_{51_{max}})-(P_{51}-P_{51_{max}})(2AP_{51}-A+1)]}{2(AP_{51}+1)^2[\gamma_1 M_1^2-(P_{51}-1)]\left[-\dfrac{A(P_{51}-P_{51_{max}})}{(AP_{51}+1)}\right]^{1/2}}\right\} \le \frac{(M_3^2-1)^{1/2}}{\gamma_3 M_3^2} \qquad (23)$$

where

$$P_{51_{max}} = \frac{\gamma_1-1}{2(\gamma_1+1)}\left\{\frac{2\gamma_1 M_1^2}{\gamma_1-1}+\frac{2}{\gamma_1-1}+\left[\left(\frac{2\gamma_1 M_1^2}{\gamma_1-1}+\frac{2}{\gamma_1-1}\right)^2-4A\left(\frac{2\gamma_1 M_1^2}{\gamma_1-1}-1\right)\right]^{1/2}\right\}$$

and

$$A = \frac{\gamma_5+1}{\gamma_5-1} = \frac{\gamma_1+1}{\gamma_1-1}$$

Equation (23) is the necessary and sufficient condition for the stability of the resulting limiting triple discontinuity configuration of the interaction problem considered.

Because the slope of the isentrope in the δ, p plane, $(d\delta/d\ell np)_R$, is always negative [see Eq. (A5)], condition (23) is always satisfied for mathematical solutions with a reflected Mach wave which are on the weak branch of the transmitted shock polar, where $(d\delta/d\ell np)_T \geq 0$ always. However, condition (23) can also be satisfied on a certain portion of the strong branch of the transmitted shock polar, where $(d\delta/d\ell np)_T < 0$, resulting in physically realizable reflected Mach wave configurations. These triple discontinuity configurations represent the limiting cases for physically possible interaction patterns with reflected shock or rarefaction waves.

Condition (23) is not satisfied at point A in Fig. 6. Hence, the reflected Mach wave interaction configuration represented by this point for the flow conditions considered, as well as points C and B corresponding to reflected shock wave and reflected rarefaction wave configurations, respectively, are not physically realizable. The only stable and physically possible solutions are given in this case by points B', A' and C'.

5. ANALYSIS OF WAVE CONFIGURATIONS

From Section 3, it is clear that the solution of the considered interaction problem reduces to finding the roots of Eq. (20), i.e. the values of P_{51} for a given set of flow parameters M_1, P_{21}, P_{32}, γ_2, γ_3 and Q_{32}. Whether the solution obtained is physically realizable or not is determined by using the criterion developed in Section 4. Moreover, the intervals within which P_{21} and P_{32} can vary depend on the oncoming flow Mach number M_1 and the fuel/air mixture considered, i.e. on γ_2, γ_3 and Q_{32}. The procedure for determining these intervals, as well as the domains of existence of the resulting physically possible interaction configurations and the strengths of the resulting

waves is *here* given for the particular case when $M_1 = 7.0$, $\gamma_1 = \gamma_2 = 1.40$, $\gamma_3 = 1.30$ and $Q_{32} = 8.0$.

It is obvious that the lower limit of the interval of variation of P_{21}, $P_{21_\ell} = 1$. The upper limit of this interval, P_{21_u}, is determined by the condition that for given M_1, γ_2, γ_3 and Q_{32} there is a Mach number M_2 in region 2 for which the detonation wave is operating at the single Chapman-Jouguet condition [see Fig. 9(d)]. Letting $M_{n3} = M_3 = 1$ in Eqs. (8)-(10) and eliminating M_{n2} and P_{32} from these equations, we get the following equation to determine M_2:

$$\frac{1}{(\gamma_3-1)^2}(\gamma_2 M_2^{\,2}+1)^2 - \frac{\gamma_3+1}{\gamma_3-1}\left[\frac{2\gamma_2 M_2^{\,2}}{\gamma_2-1}(1+\gamma_2 Q_{32})-1\right] = 0 \qquad (21)$$

Elimination of M_{2n} from Eqs. (8) and (9) will then yield an equation from which the value P_{21_u} is computed. For the numerical example considered $M_2 = 5.4$ and $P_{21_u} = 4.04$.

For each value of P_{21} in the interval $P_{21_\ell} < P_{21} < P_{21_u}$, and hence for each value of M_2 between $M_{2_u} = M_1$ (when $P_{21} = P_{21_\ell} = 1$) and M_{2_ℓ} (when $P_{21} = P_{21_u}$) determined from Eq. (21), we can plot detonation polars, as shown in Fig. 7. For strong detonation waves considered in the present Note, the lower limit of the interval of variation of P_{32}, P_{32_ℓ}, should be its Chapman-Jouguet value given by Eq. (14), $P_{32_\ell} = P_{32_{CJ}}$ (= 17.85 for the numerical example considered). The upper limit for the variation of P_{32}, P_{32_u}, is given by the condition $M_3 = 1$. Eliminating again M_{2n} from Eqs. (8) and (9) and letting $M_3 = 1$, we arrive at an equation from which the value $P_{32_u} = P_{32_s}$, i.e. the value of P_{32} *giving sonic flow behind the* detonation wave, is obtained. It should be noted that this value of P_{32_s} is a function of P_{21}. Figure 8 depicts the domain of variation of P_{21} and P_{32} for the specific numerical example treated (shaded area). The horizontal line AB represents the lower, constant, Chapman-Jouguet limit of P_{32}. The curve BEC is the locus of values of P_{32_s}, and the curve BFG that of $P_{32_{max}}$ (resulting in normal detonation waves). The curve DHE is the locus of pairs of values of P_{21} and P_{32} of the strength of the interacting shock and detonation waves which result in a configuration with a reflected Mach wave

Numerical calculations show that for all these solutions on line DHE the criterion (23) is not satisfied. Therefore they are not physically realizable. On the other hand, calculations show that, for every point in the domain ABEC (Fig. 8), there is a solution with a reflected rarefaction wave. Figures 9(a)-(d) show the graphical solution of the interaction problems with reflected rarefaction waves. Note that in Fig. 9(d) the detonation polar has shrunk to a point. The strengths of the transmitted shock waves and reflected rarefaction waves for different values of the strengths of the interacting waves are plotted in Figs. 10(a)-(d).* For the numerical example considered, it has been found that all physically possible interactions result in configurations with a reflected rarefaction wave.

*Tables of numerical values of strengths of all waves involved in the interaction process and the corresponding Mach numbers in different flow regions for the range of values: $M_1 = 6, 7, 8$; $Q_{32} = 3, 4, 5, 6, 7, 8$ and $\gamma_3 = 1.30$, 1.315, 1.33 are available upon request from UTIAS.

Similar calculations were performed for different values of M_1 and Q_{32}. The corresponding domains of existence of interaction configurations with a reflected rarefaction wave are presented in Figs. 11(a)-(j) (areas under the corresponding curves). It should be noted that as the values of the heat release parameter are decreased the upper limit of the interval of variation of P_{32} ceases to be P_{32s}, as the epicycloid III describing the rarefaction wave issuing from the point P_{32s} on the detonation polar II does not intersect the shock polar I, and therefore, there is no solution of the interaction problem. This is clear from the graphical solution presented in Fig. 12. For $P_{32} = P_{32CJ} = P_{32\ell} = 15.74$ or for $P_{32} = 22.0$ there are solutions represented by the points A and B, respectively, in the polar I, whereas for $P_{32} = 29.0 < P_{32s}$, there is no solution. In these cases the upper limit of the interval of variation of P_{32} is determined numerically as the point where the roots of Eq. (20), if they exist, coincide. The domain of existence of reflected rarefaction wave configurations is then represented by the area under the line ABCDE in Fig. 11(b).

If we further decrease the value of Q_{32} (for example, $Q_{32} = 4$ and $M_1 = 8$) the aforementioned domain of existence splits in two subdomains ABCGK and DHE [see Fig. 11(e)]. There are no solutions for P_{21} in the interval GH and for $P_{32} \geq P_{32CJ}$. The reason for this splitting is clear from the graphical solution presented in Fig. 13. This figure depicts the case when P_{32} is kept constant at $P_{32} = P_{32CJ}$ and P_{21} assigned the values: $P_{21} = 11.5$, 13.0 and 14.5. The corresponding epicycloids for the reflected rarefaction waves issuing from points $P_{32} = P_{32CJ}$ intersect the shock polar I for $P_{21} = 11.5$ and 14.5 but not for the intermediate value $P_{21} = 13.0$.

Stable, and hence physically possible, reflected Mach wave configurations have been found to exist for very low values of the heat release parameter Q_{32}. Figure 14 presents results of numerical calculations for the case $M_1 = 7$, $\gamma_1 = \gamma_2 = 1.4$, $\gamma_3 = 1.33$ and $Q_{32} = 1.0$. Curve EDC is the locus of stable [according to criterion (23)], and hence physically realizable, reflected Mach wave configurations separating regions where stable interaction configurations with reflected shock (area EDCF) and rarefaction waves (area EDCGBA) occur. Points on the ED portion of this curve correspond to configurations with transmitted shock waves on the weak branch of the shock polar, whereas for points on the DC portion, the transmitted shock wave is on the strong branch of the shock polar. There are no regular interaction solutions in the region above the curve BGCF. Curve HIJ is the locus of points for which the Mach number behind the detonation wave is exactly sonic, $M_3 = 1$.

It is of interest to consider the particular case when $P_{21} = 1.0$, always (line AEF in Fig. 14). The problem then reduces to the refraction of a detonation wave at a combustible/non-combustible gas interface. The equilibration of pressures behind the detonation wave and the shock wave (to which the detonation wave degenerates in the non-combustible gas mixture) is achieved through a shock wave if the strength of the detonation wave P_{32} lies in the interval EF, and through a rarefaction wave if P_{32} is in the interval AE. Point E corresponds to a double discontinuity situation, i.e. only the detonation and the shock waves are present, the equilibration of pressures taking place across a Mach wave. Thus for the case considered (where $\gamma_1 = \gamma_2 = \gamma_5 \neq \gamma_3$) such a double discontinuity configuration, with energy addition on one of the discontinuities, is possible. Rues (Ref. 6) has shown that for $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_5$ such a configuration is impossible. Calculations performed for the particular case considered, assuming constant

specific ratio everywhere, have also shown that such a double-discontinuity configuration does not exist. This example again shows the importance of the value of the specific heat ratio of the combustion products γ_3 for the interaction problem considered.

6. DISCUSSION AND CONCLUSIONS

The transmitted shock wave is usually on the weak solution branch of the shock polar. However, when P_{32} approaches P_{32_u}, the transmitted shock wave may be on the strong solution branch, as exemplified by Fig. 15. Both theoretical solutions are on the strong branch of the shock polar with $P_{51} = 66.44$ and 65.46; the latter solution is physically possible according to solution continuity arguments.

The upper limit of the interval of variation of P_{21}, P_{21_u}, is fixed by the Chapman-Jouguet condition of the detonation wave. The higher the oncoming flow Mach number and the lower the value of the heat release parameter of the detonation wave, the larger P_{21_u} is. When P_{21_u} is large, for some values of the incident shock wave strength, P_{21}, there is no solution to the regular interaction problem considered and the interval of variation of P_{21} becomes discontinuous.

In the problem of the interaction of a shock wave with a detonation wave which deflect the flow in the same direction, of primary interest is the determination of the nature of the reflected wave. It has been found that for most combustible mixtures of gases ($3 \leq Q_{32} \leq 8$; $1.30 \leq \gamma_3 \leq 1.33$) the reflected wave is always a rarefaction wave. Using criterion (23), it has been shown that triple *discontinuity configurations* (reflected Mach wave) and hence configurations with a reflected shock wave and rarefaction wave) are physically possible for combustible gases with low heat release and are very sensitive to the values of the specific heat ratio of the combustion products behind the detonation wave. Considering the particular case of refraction of a detonation wave at a combustible/non-combustible gas interface, it has been found that for low values of Q_{32} ($Q_{32} = 1.0$) and $\gamma_1 = \gamma_2 = \gamma_5 \neq \gamma_3$ double discontinuity configurations, where only the detonation and shock waves are present (the equilibration of pressures behind the detonation and shock waves takes place across a Mach wave), can exist.

In general, the magnitudes of the heat release parameter, Q_{32}, and specific heat ratio, γ_3, of the combustion products behind the detonation wave affect significantly the interaction pattern of shock and detonation waves. It is, therefore, concluded that for given particular flow configuration of the interacting shock and detonation waves and combustible mixture of gases, a detailed thermochemical analysis be made in order to determine the actual values of the heat release parameter, Q_{32}, and the specific heat ratio of the combustion product, γ_3. The nature of the resulting interaction pattern could then be established by using these actual values of Q_{32} and γ_3.

The interaction problem considered in the present Note was also investigated by Rues (Ref. 7) for the particular case when the resulting interaction pattern involves only a reflected Mach wave; no allowance was made for the change of specific heat ratios across the detonation wave. For this particular situation, the results obtained in the present work

coincide with those of Ref. 7. However, according to criterion (23), all triple discontinuity configurations studied by Rues are not stable and hence physically not realizable. When $Q_{32} = 0$ and $\gamma_2 = \gamma_3 = 1.4$, the results obtained in the present Note coincide with those of Ref. 8, where the similar interaction problem of two shock waves is considered.

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APPENDIX

DERIVATION OF THE DERIVATIVES OF THE FLOW DEFLECTION ANGLE THROUGH THE WAVE WITH RESPECT TO THE PRESSURE BEHIND THE WAVE

For the general case of a detonation wave, the flow deflection angle through the wave, Eq. (15), can be rewritten as:

$$\delta = \pm \tan^{-1}\left\{\frac{P-1}{\gamma_1 M_1^2 - (P-1)}\left[-\frac{A(P-P_{max})(P-P_{min})}{(P-1)(AP+1)}\right]^{1/2}\right\} \quad \text{(A1)}$$

where $P = p/p_1$, p = pressure behind the wave, $A = \gamma_2+1/\gamma_2-1$, and

$$P_{\substack{max\\min}} = \frac{\gamma_1 M_1^2}{\gamma_2+1} + \frac{1}{\gamma_2+1} \pm \left\{\left(\frac{\gamma_1 M_1^2}{\gamma_2+1} + \frac{1}{\gamma_2+1}\right)^2 - \frac{1}{A}\left[\frac{2\gamma_1 M_1^2}{\gamma_1-1}(1+\gamma_1 Q) - 1\right]\right\}^{1/2} \quad \text{(A2)}$$

subscript 2 denoting the flow region behind the wave. From Eq. (A1) we have

$$\pm\frac{d\delta}{dp} = \frac{\cos^2\delta}{p_1}\left\{\frac{\gamma_1 M_1^2}{[\gamma_1 M_1^2 - (P-1)]^2}\left[-\frac{A(P-P_{max})(P-P_{min})}{(P-1)(AP+1)}\right]^{1/2} - \right.$$

$$\left. - \frac{A[(P-1)(AP+1)(2P-P_{max}-P_{min}) - (P-P_{max})(P-P_{min})(2AP-A+1)}{2(P-1)(AP+1)^2[\gamma_1 M_1^2 - (P-1)]\left[-\frac{A(P-P_{max})(P-P_{min})}{(P-1)(AP+1)}\right]^{1/2}}\right. \quad \text{(A3)}$$

where the + sign corresponds to the right-half of the detonation wave polar. Taking into account Eq. (A1), the above equation can be finally written in the form

$$\pm\frac{d\delta}{d\ell nP} = \frac{P}{\left\{1 - \frac{A(P-1)(P-P_{max})(P-P_{min})}{[\gamma_1 M_1^2 - (P-1)]^2(AP+1)}\right\}}\left\{\frac{\gamma_1 M_1^2}{[\gamma_1 M_1^2 - (P-1)]^2} \times \right.$$

$$\times\left[-\frac{A(P-P_{max})(P-P_{min})}{(P-1)(AP+1)}\right]^{1/2} -$$

$$\left. - \frac{A[(P-1)(AP+1)(2P-P_{max}-P_{min}) - (P-P_{max})(P-P_{min})(2AP-A+1)}{2(P-1)(AP+1)^2[\gamma_1 M_1^2 - (P-1)]\left[-\frac{A(P-P_{max})(P-P_{min})}{(P-1)(AP+1)}\right]^{1/2}}\right\} \quad \text{(A4)}$$

Equation (A4) gives also the value of the derivative in the case of a shock wave if we let $Q = 0$, $\gamma_1 = \gamma_2$ and $P_{min} = 1$.

For isentropic rarefaction or compression waves, we have (see, for example, Ref. 9, p. 422)

$$\frac{d\delta}{d\ell np} = - \frac{\sqrt{M^2-1}}{\gamma M^2} \tag{A5}$$

where δ is assumed positive when it increases in the clockwise direction. Hence $d\delta/d\ell np$ for an isentropic wave is always negative. Letting $d(d\delta/d\ell np)/dM = 0$, we will have

$$\left|\frac{d\delta}{d\ell np}\right| \leq \frac{1}{2\gamma} \tag{A6}$$

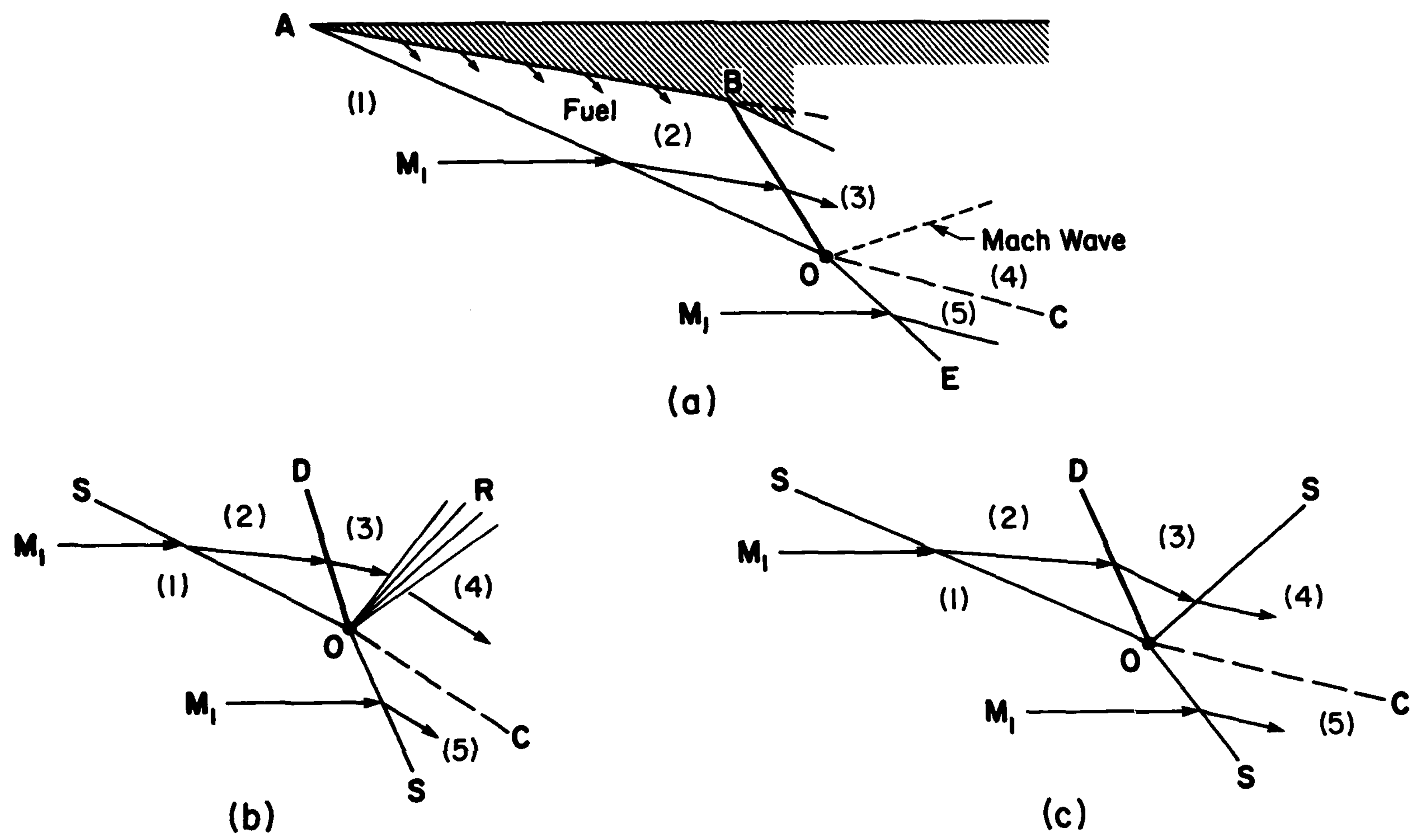

FIG. 1. POSSIBLE DISCONTINUITY CONFIGURATIONS RESULTING FROM THE INTERACTION OF A SHOCK WAVE WITH A DETONATION WAVE. S-SHOCK WAVE, D-DETONATION WAVE, R-RAREFACTION WAVE, C-CONTACT DISCONTINUITY. (a) CONFIGURATION WITH A REFLECTED MACH WAVE; (b) CONFIGURATION WITH A REFLECTED RAREFACTION WAVE; (c) CONFIGURATION WITH A REFLECTED SHOCK WAVE.

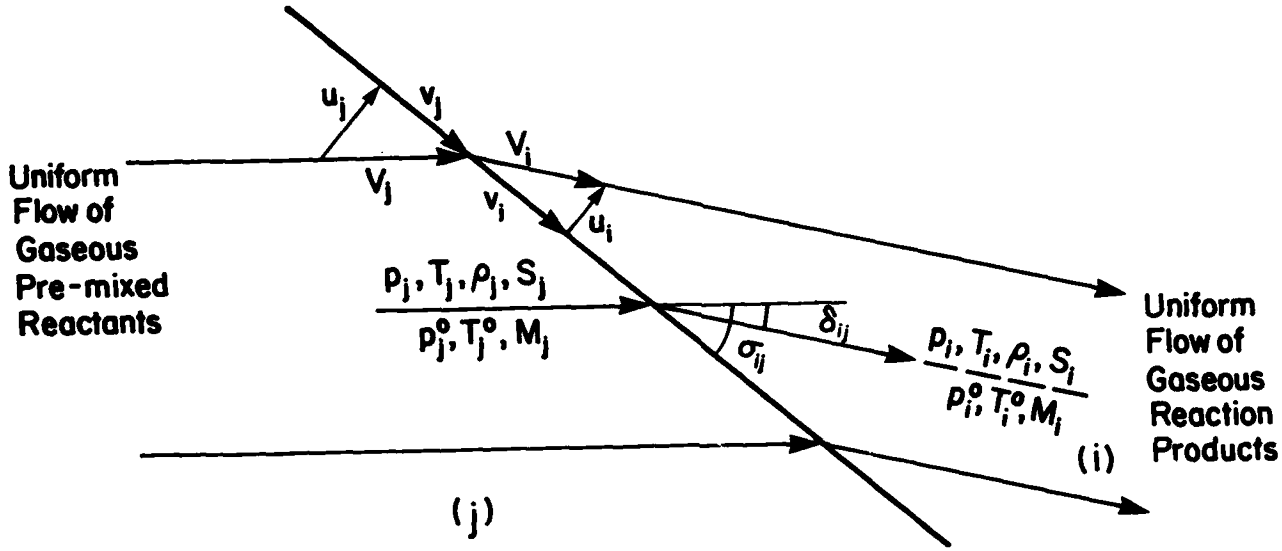

FIG. 2. PLANE OBLIQUE DETONATION FLOW MODEL.

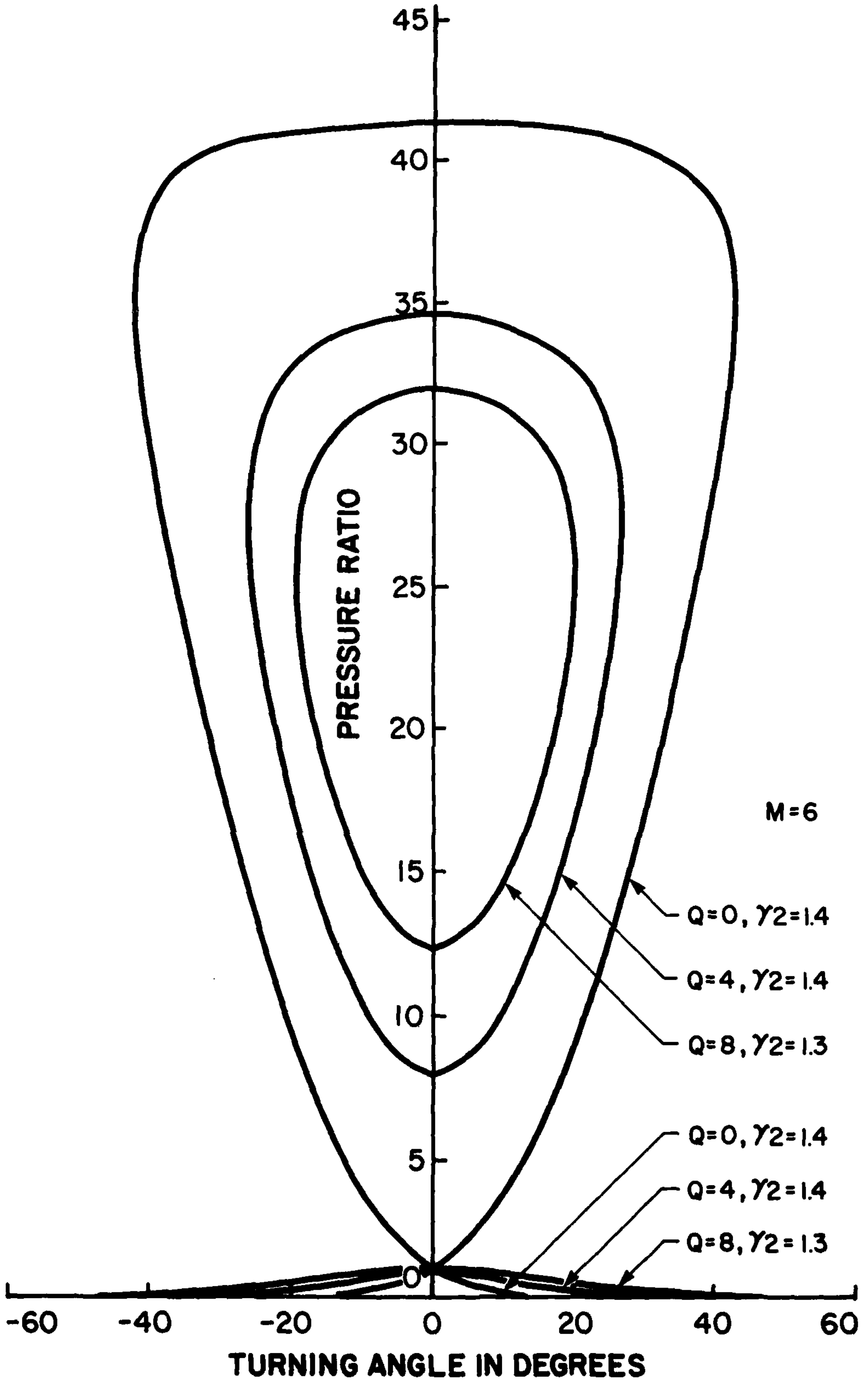

FIG. 3. OBLIQUE DETONATION AND DEFLAGRATION WAVE POLARS FOR DIFFERENT VALUES OF THE HEAT RELEASE PARAMETER Q AND SPECIFIC HEAT RATIOS γ_2.

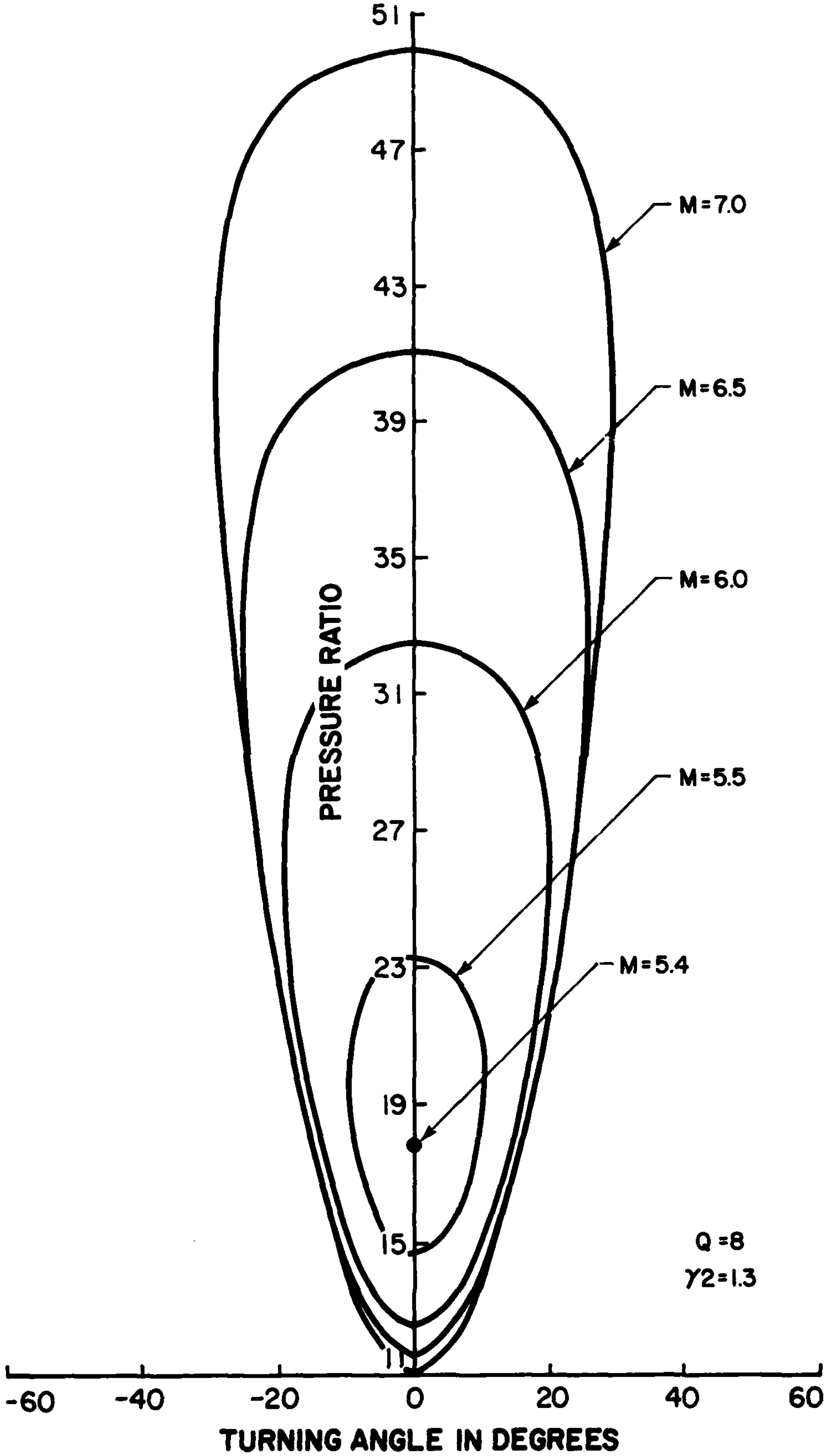

FIG. 4. OBLIQUE DETONATION WAVE POLARS FOR DIFFERENT VALUES OF THE ONCOMING FLOW MACH NUMBER.

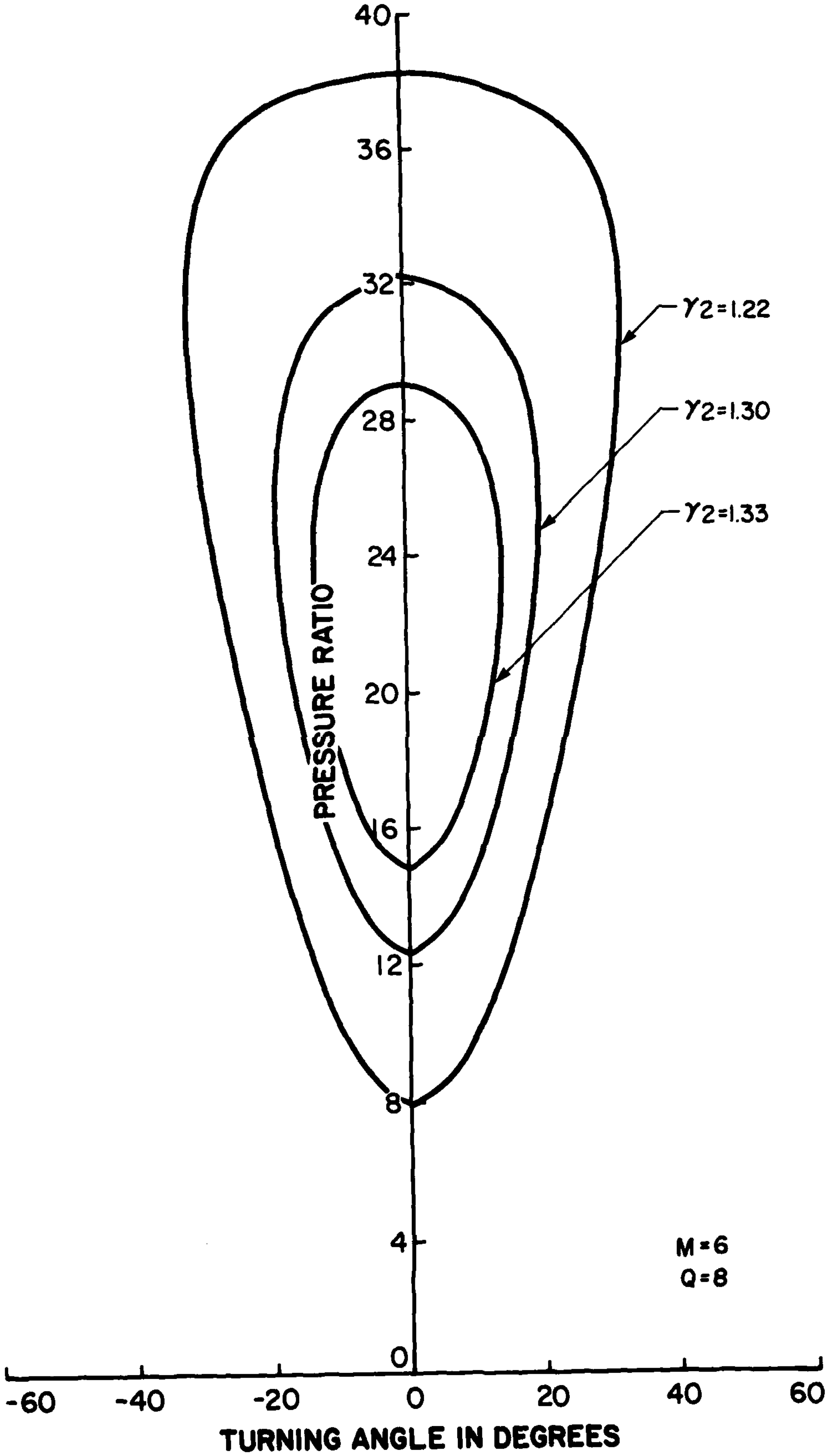

FIG. 5. OBLIQUE DETONATION WAVE POLARS FOR DIFFERENT VALUES OF THE SPECIFIC HEAT RATIO OF COMBUSTION PRODUCTS.

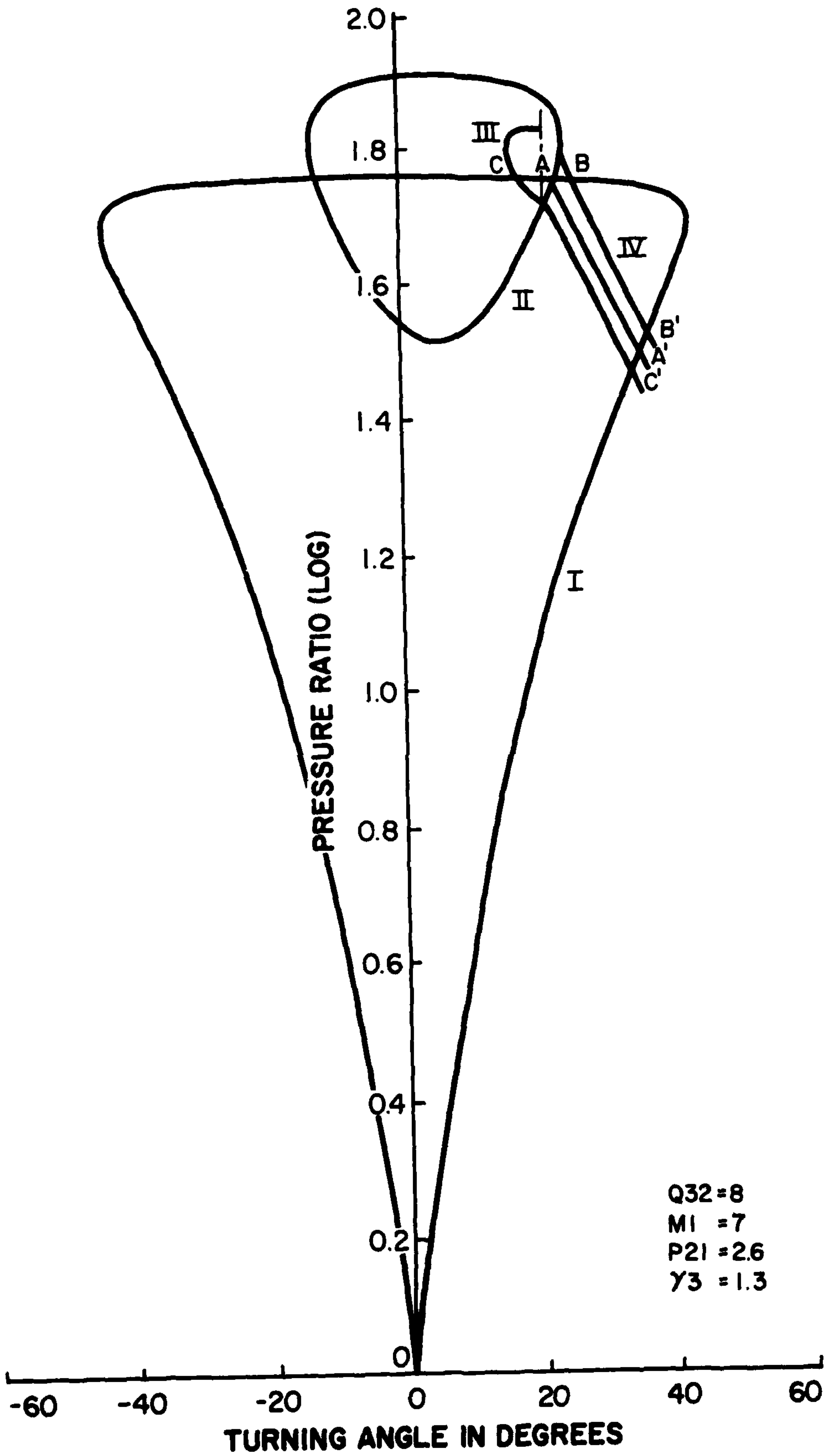

FIG. 6. INTERACTION OF A DETONATION WAVE WITH A SHOCK WAVE FOR DIFFERENT VALUES OF P_{32}.

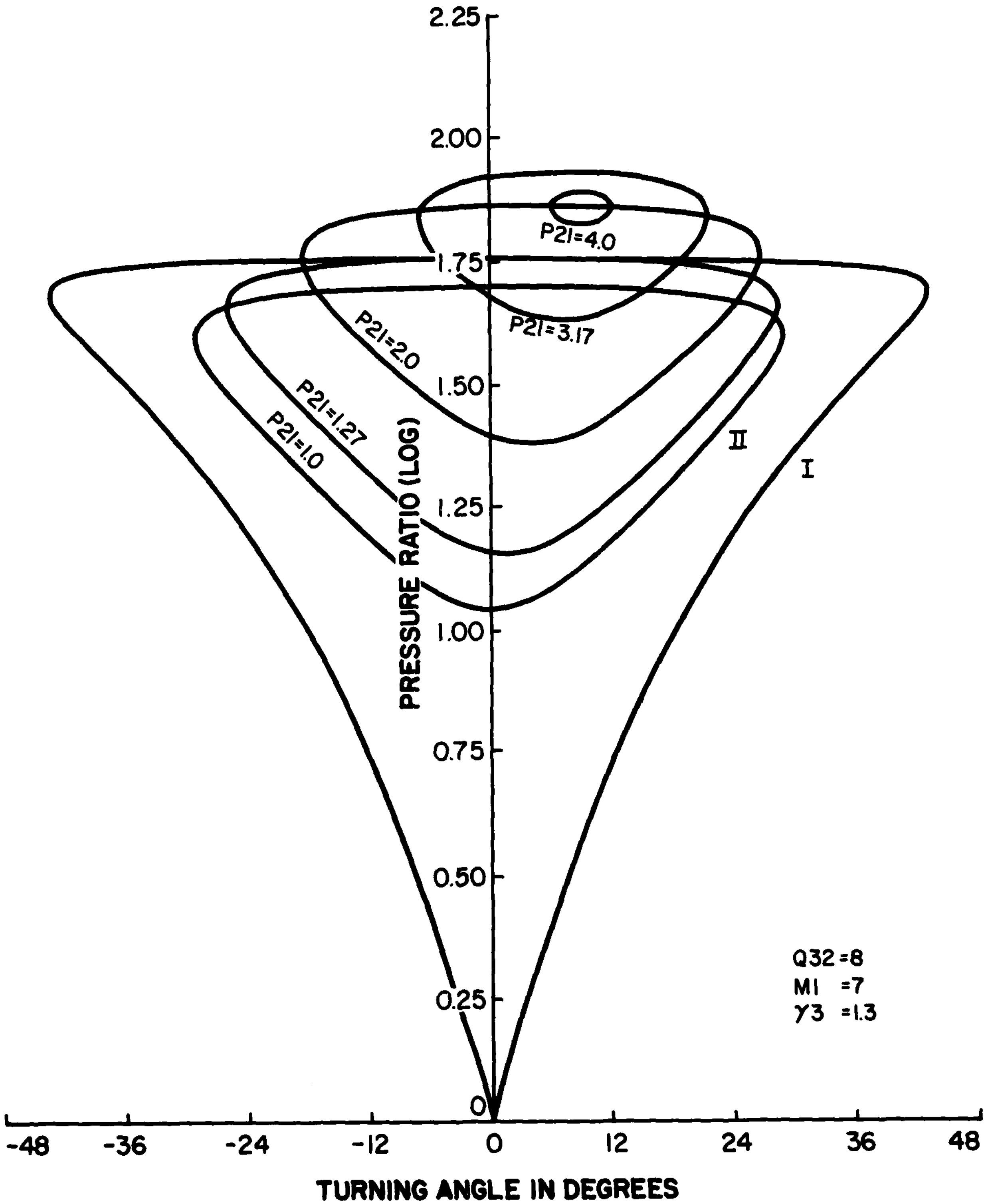

FIG. 7. SHOCK AND DETONATION POLARS FOR DIFFERENT VALUES OF P_{21}.

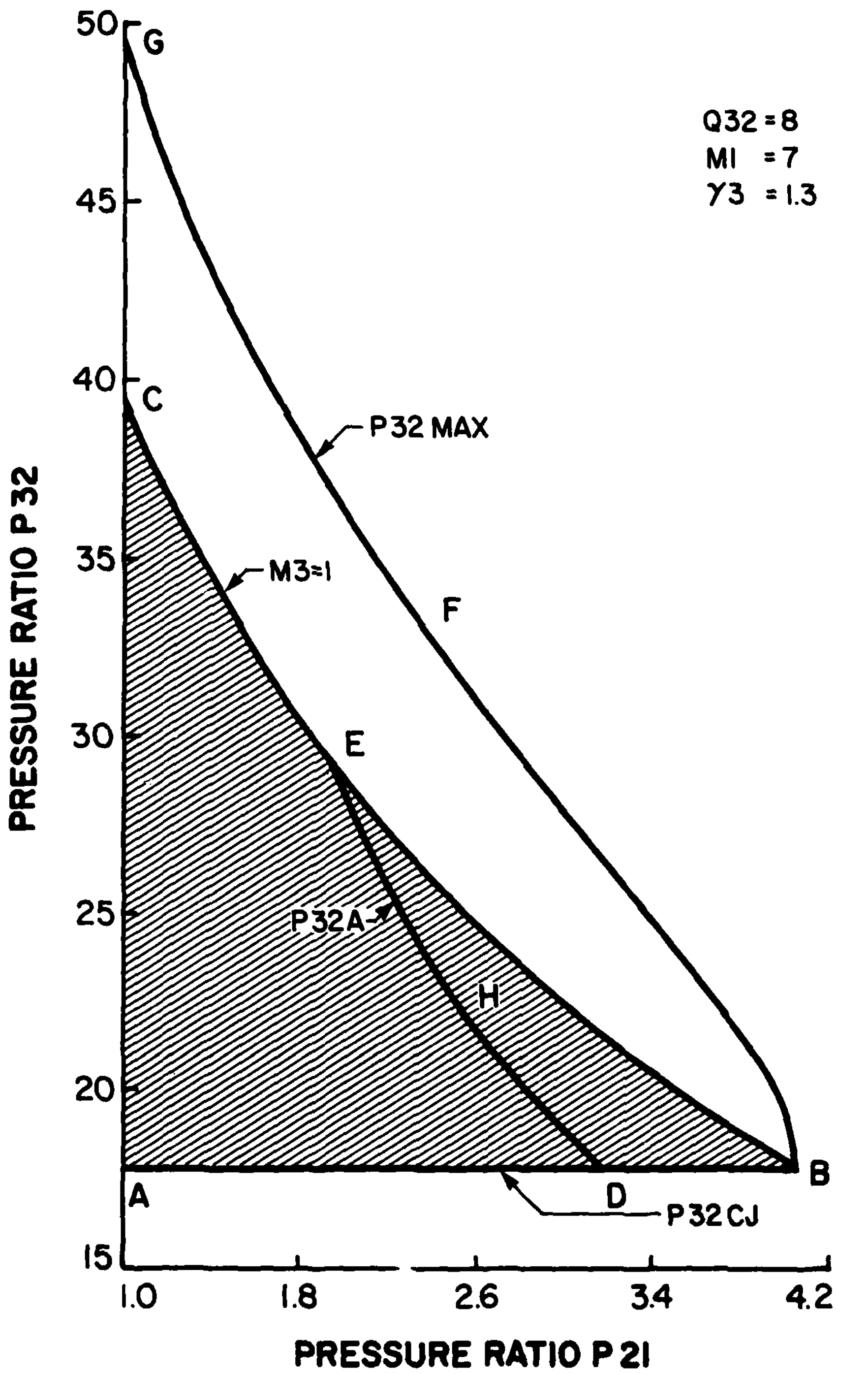

FIG. 8. DOMAIN OF EXISTENCE (SHADED AREA) OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION IN THE P_{21}, P_{32} PLANE.

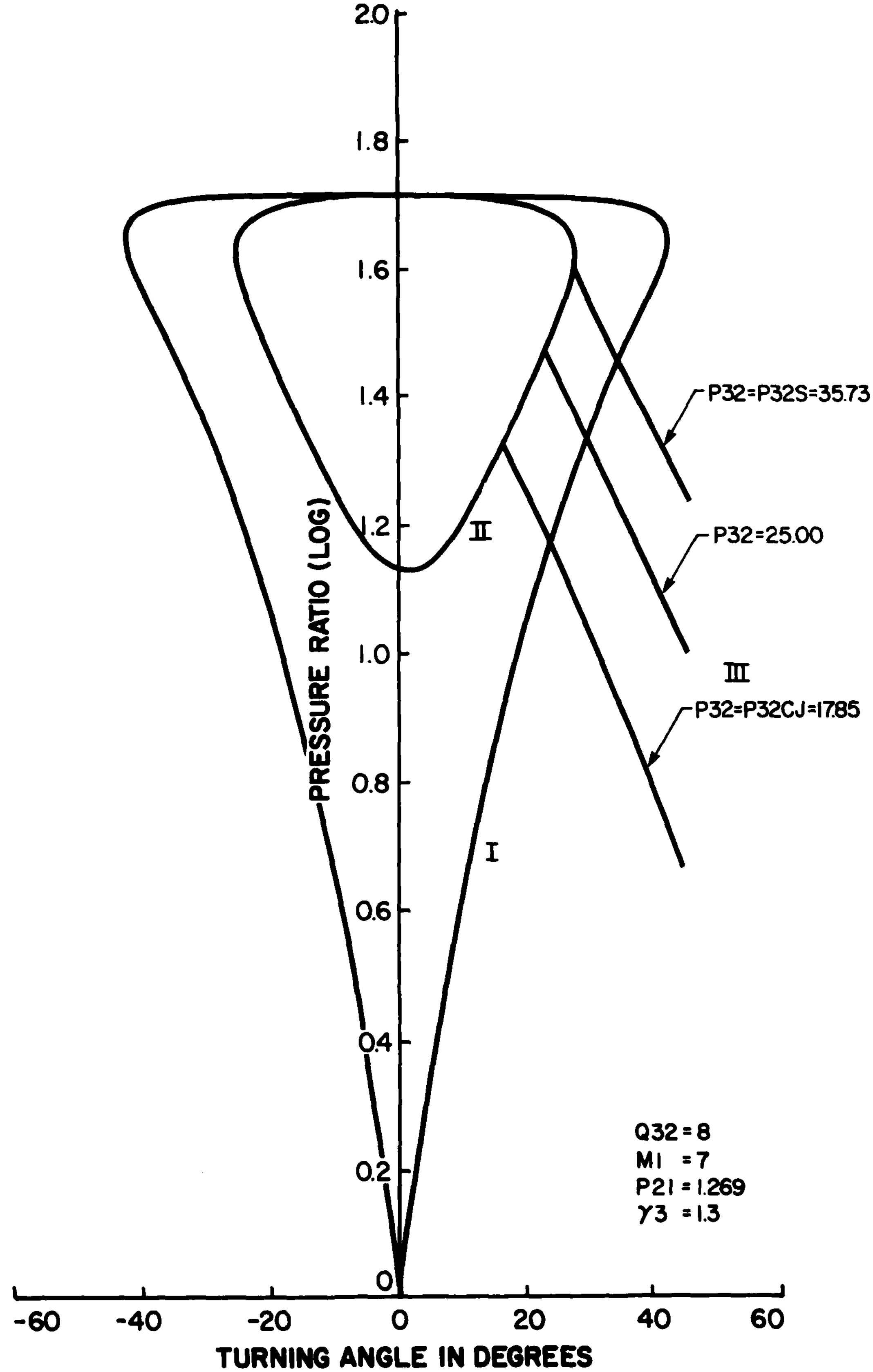

FIG. 9(a). GRAPHICAL SOLUTION OF THE INTERACTION OF A DETONATION WAVE WITH A SHOCK WAVE FOR DIFFERENT P_{32}.

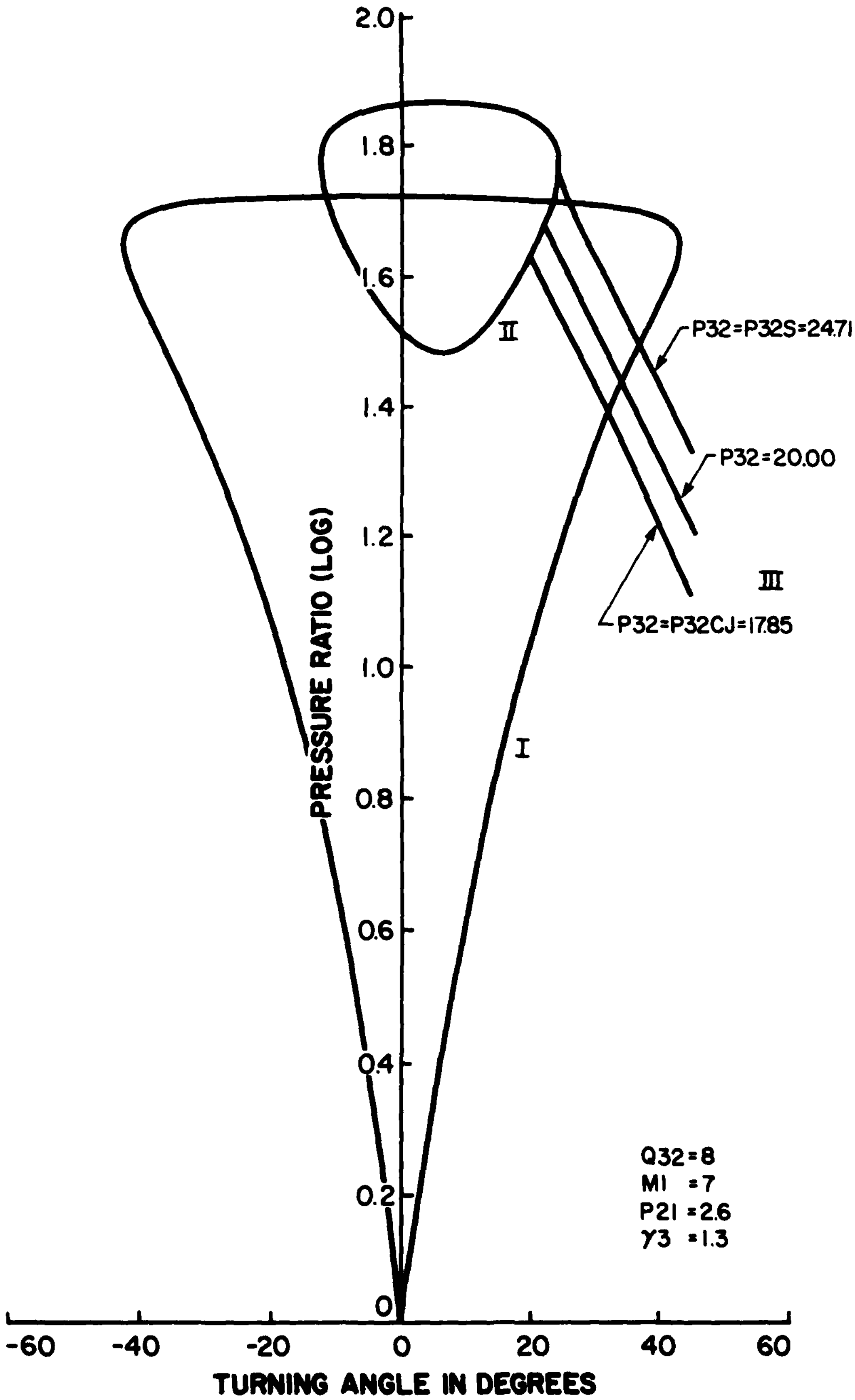

FIG. 9(b). GRAPHICAL SOLUTION OF THE INTERACTION OF A DETONATION WAVE WITH A SHOCK WAVE FOR DIFFERENT P_{32}.

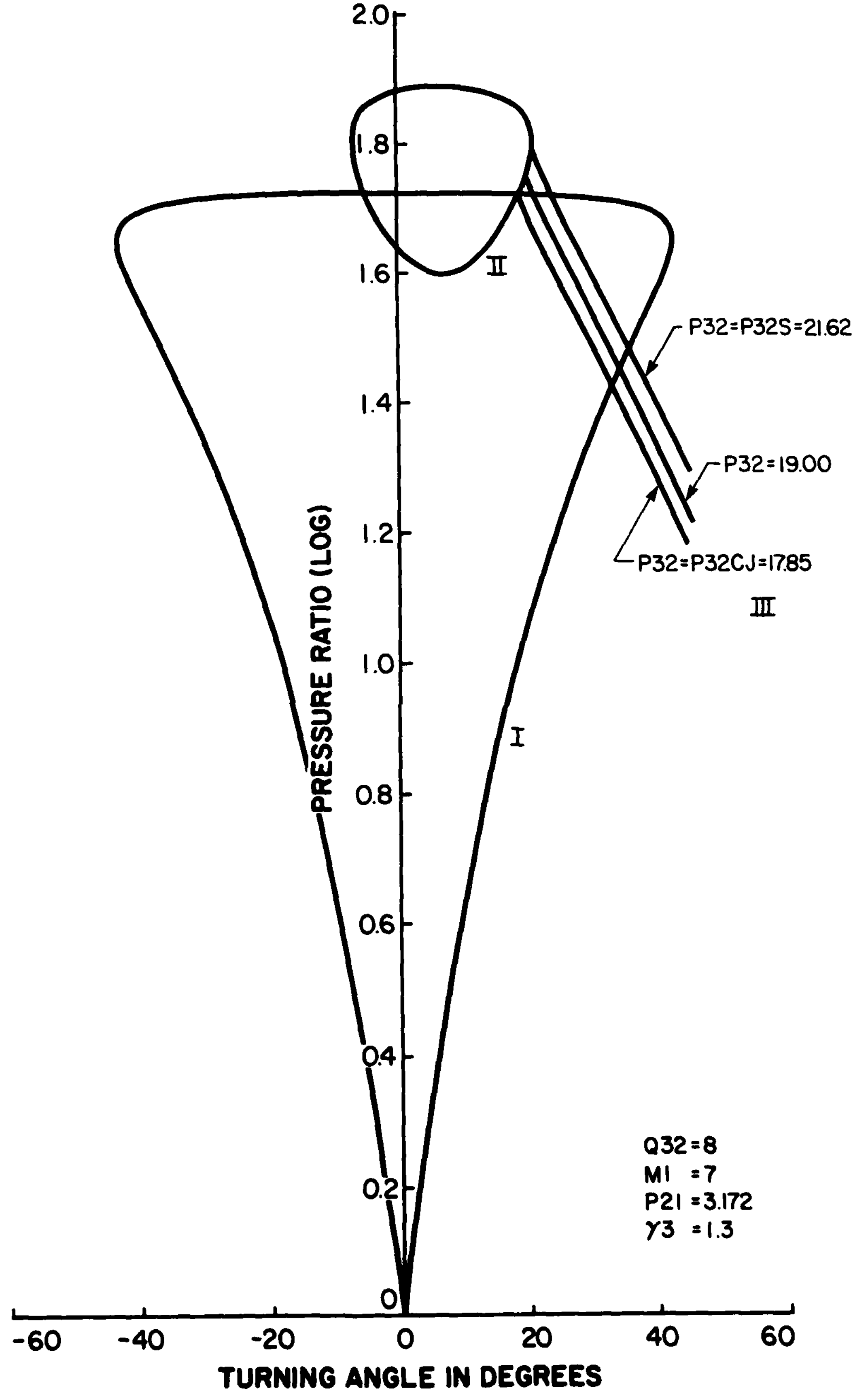

FIG. 9(c). GRAPHICAL SOLUTION OF THE INTERACTION OF A DETONATION WAVE WITH A SHOCK WAVE FOR DIFFERENT P_{32}.

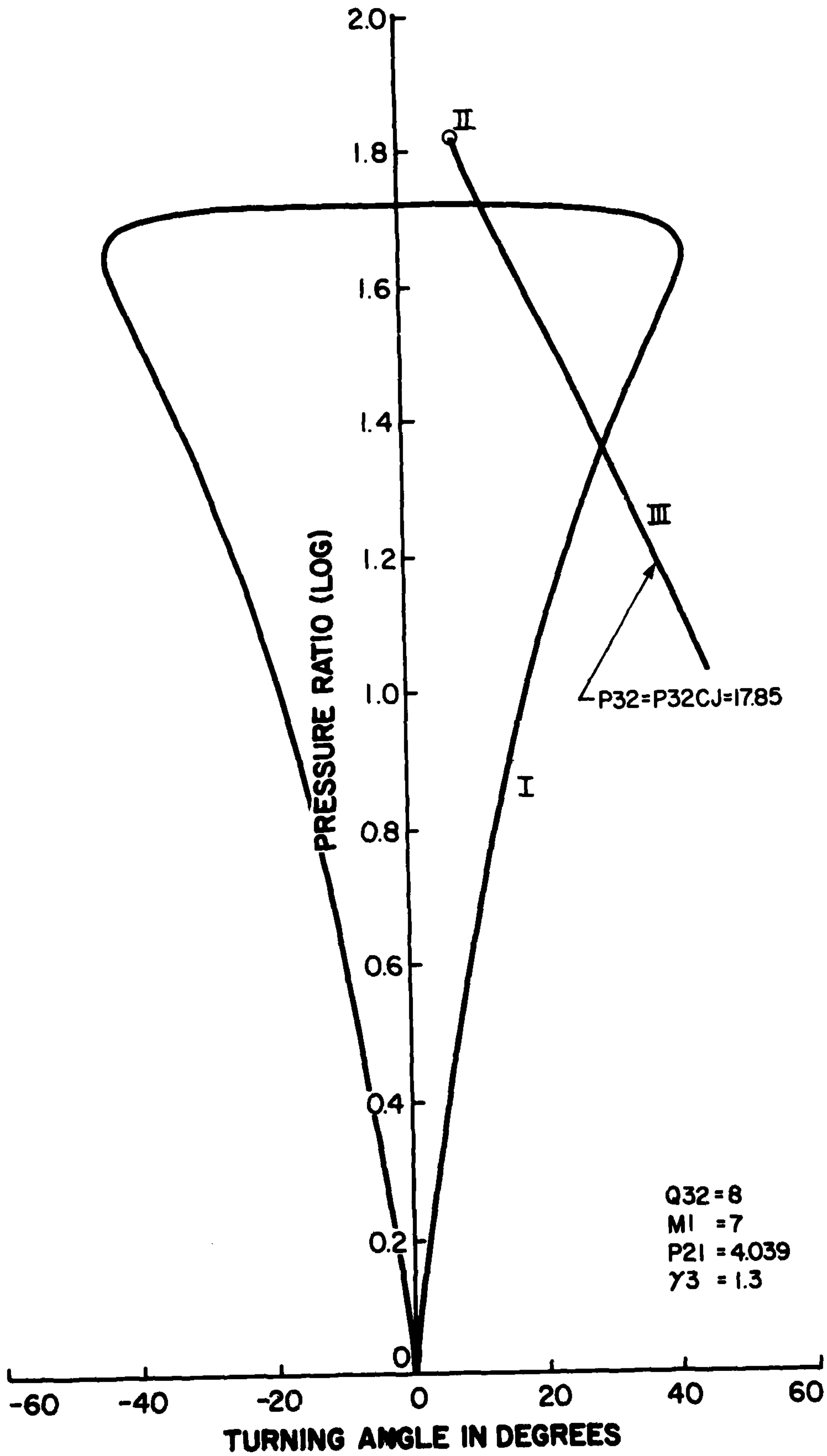

FIG. 9(d). GRAPHICAL SOLUTION OF THE INTERACTION OF A DETONATION WAVE WITH A SHOCK WAVE AT $P_{21} = P_{21_u}$.

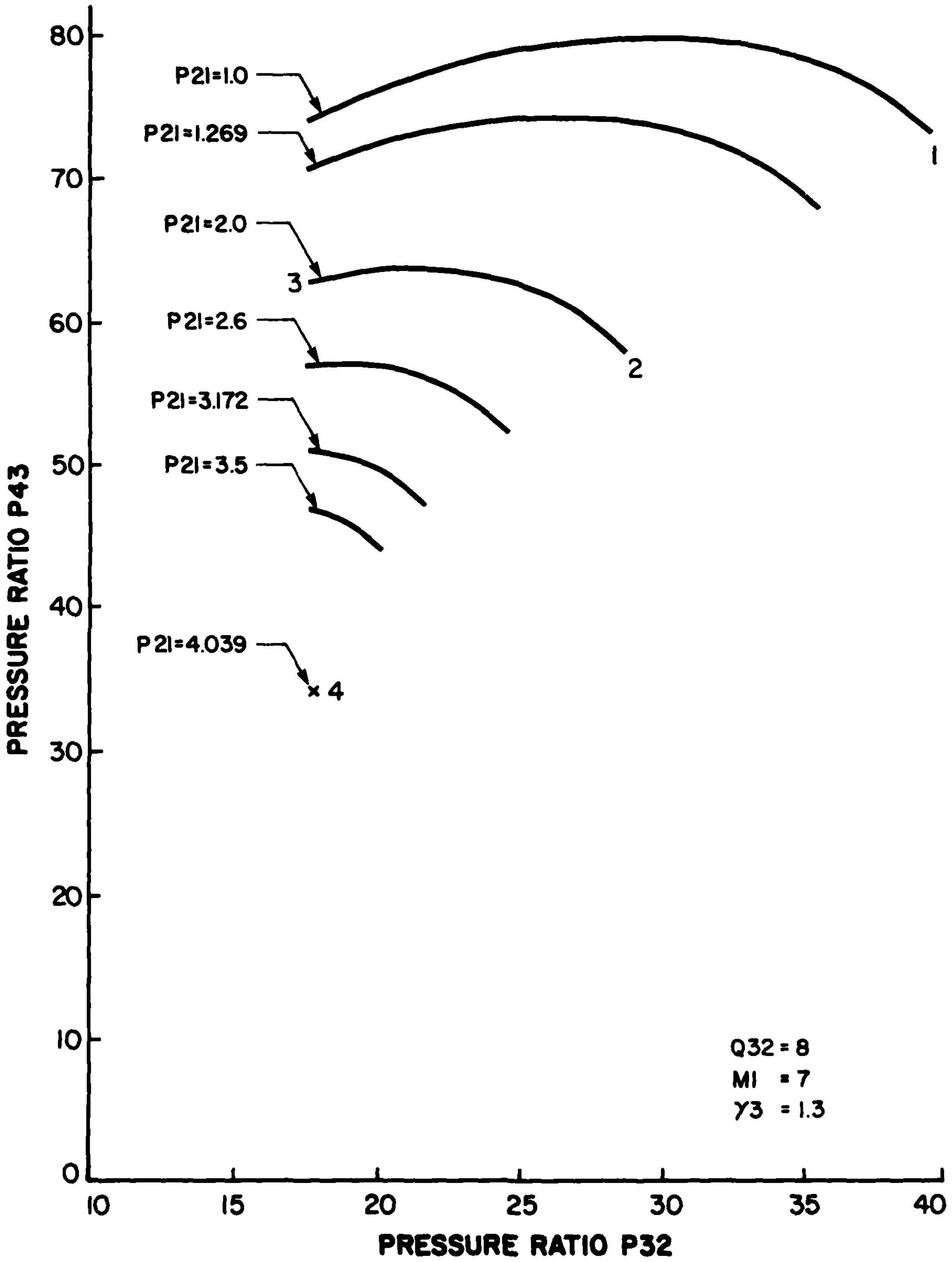

FIG. 10(a). PRESSURE RATIO ACROSS REFLECTED RAREFACTION WAVES AS A FUNCTION OF PRESSURE RATIOS ACROSS DETONATION WAVE FOR DIFFERENT SHOCK WAVE STRENGTHS.

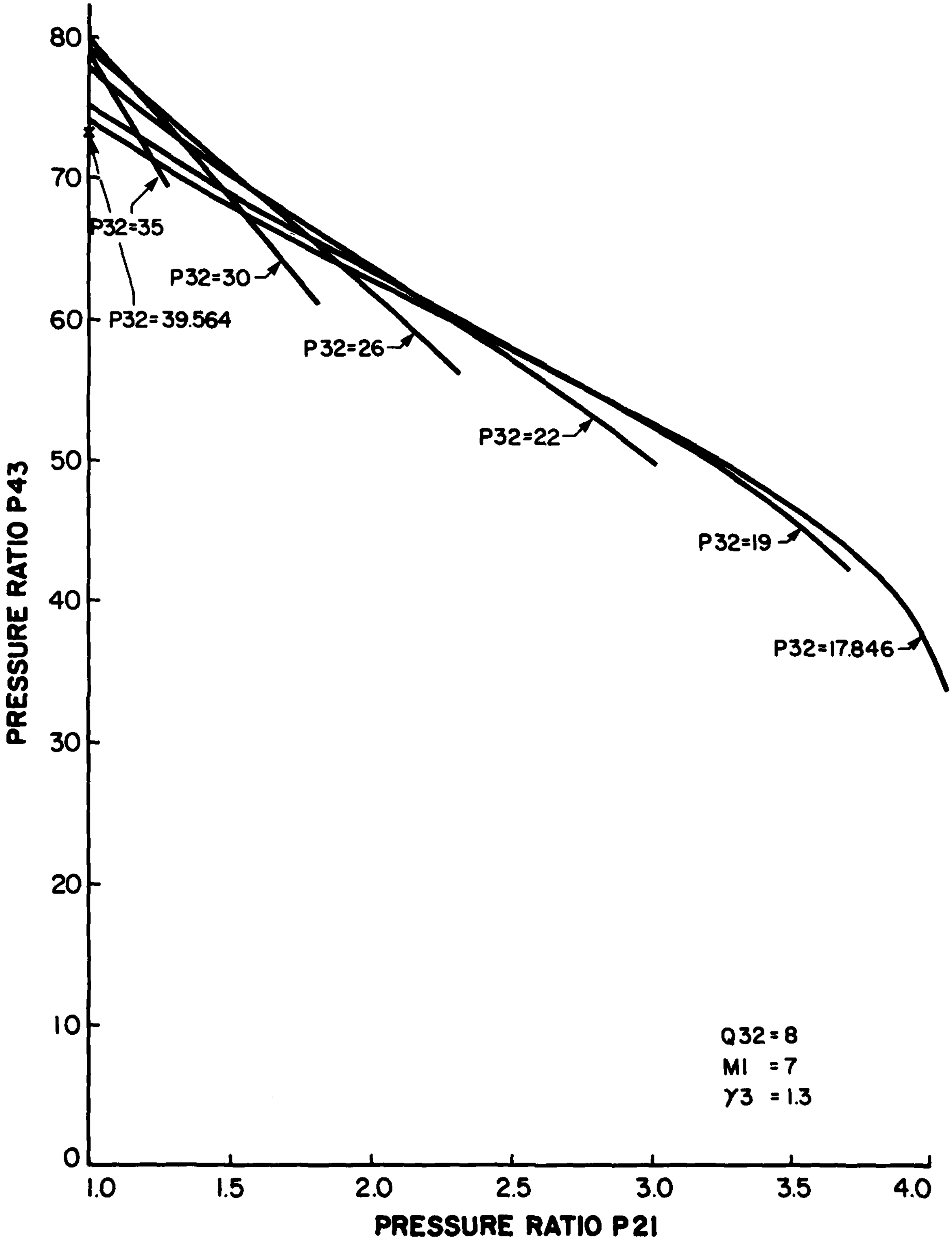

FIG. 10(b). PRESSURE RATIO ACROSS REFLECTED RAREFACTION WAVES AS A FUNCTION OF PRESSURE RATIOS ACROSS SHOCK WAVE FOR DIFFERENT DETONATION WAVE STRENGTHS.

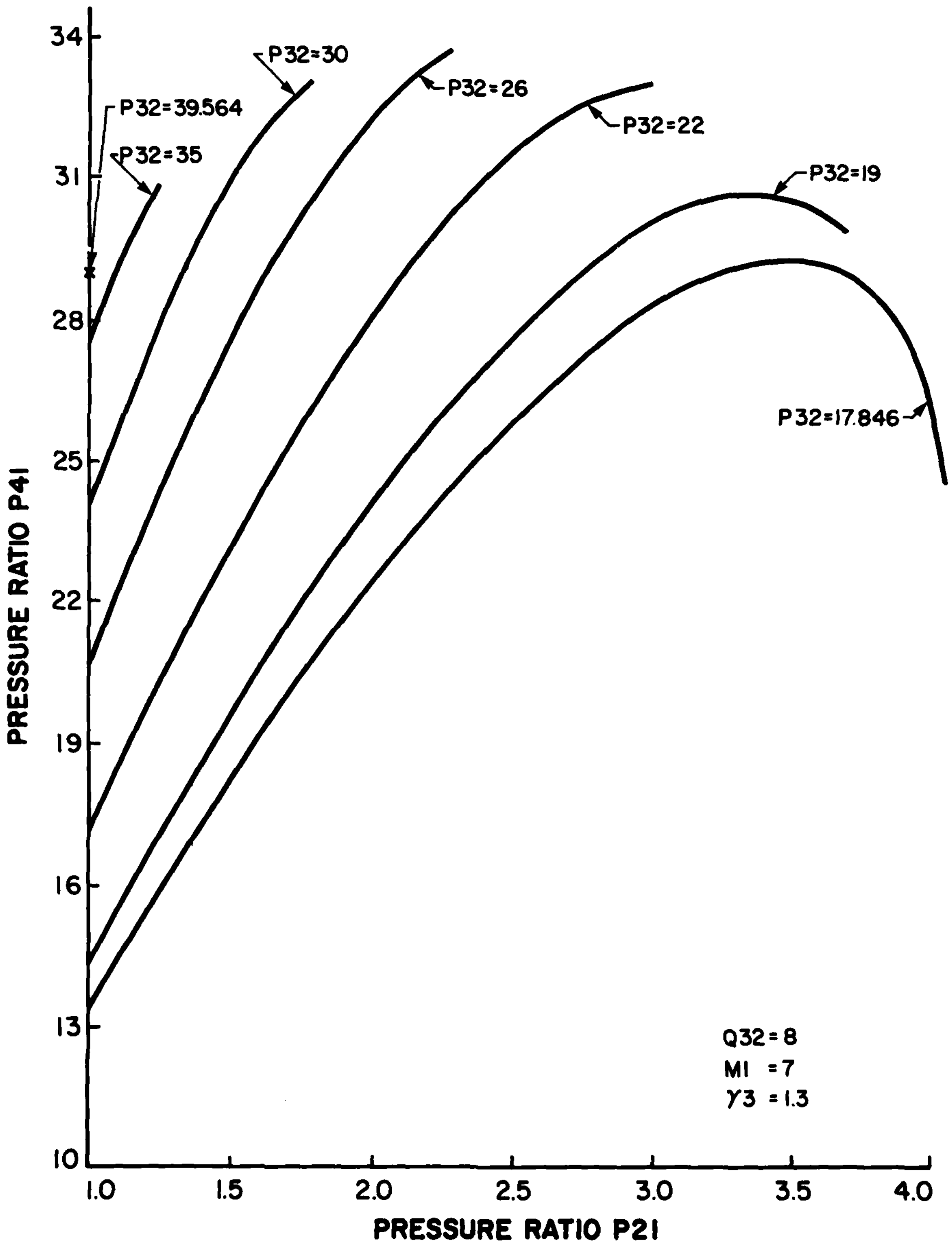

FIG. 10(c). PRESSURE RATIO ACROSS TRANSMITTED SHOCK WAVE AS A FUNCTION OF PRESSURE RATIOS ACROSS SHOCK WAVE FOR DIFFERENT DETONATION WAVE STRENGTHS.

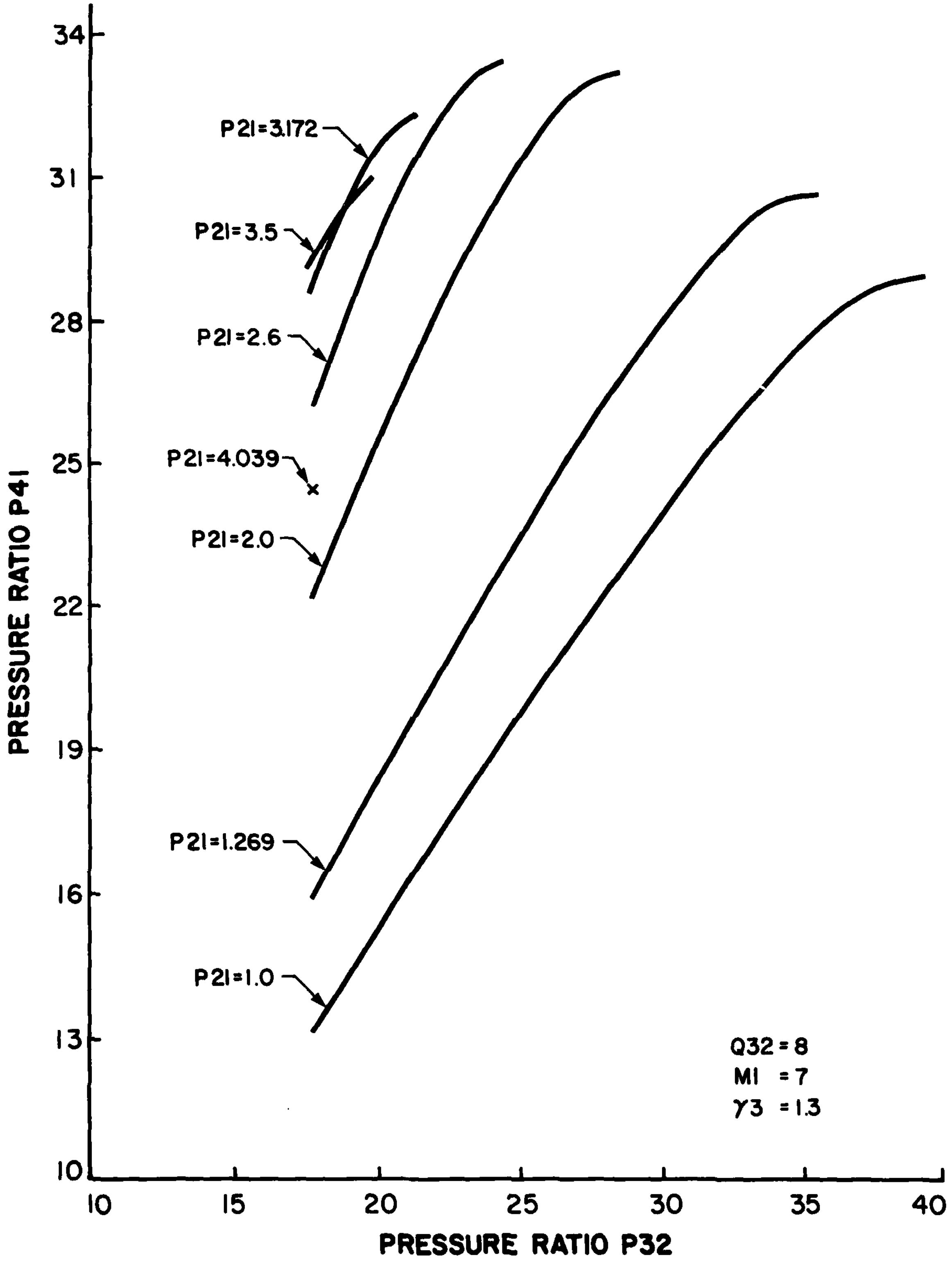

FIG. 10(d). PRESSURE RATIO ACROSS TRANSMITTED SHOCK WAVE AS A FUNCTION OF PRESSURE RATIOS ACROSS DETONATION WAVE FOR DIFFERENT SHOCK WAVE STRENGTHS.

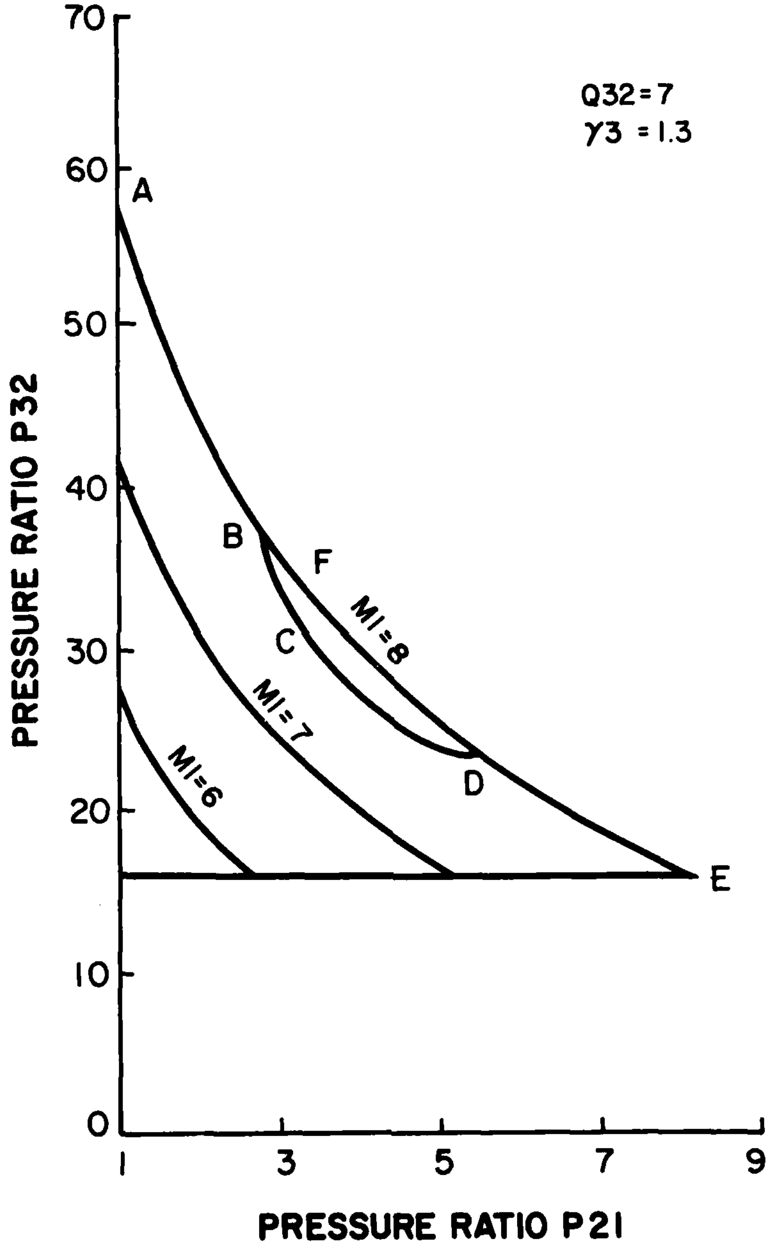

FIG. 11(a). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P_{21}, P_{32} PLANE FOR DIFFERENT VALUES OF THE ONCOMING FLOW MACH NUMBER M_1 (AREAS UNDER THE CORRESPONDING CURVES).

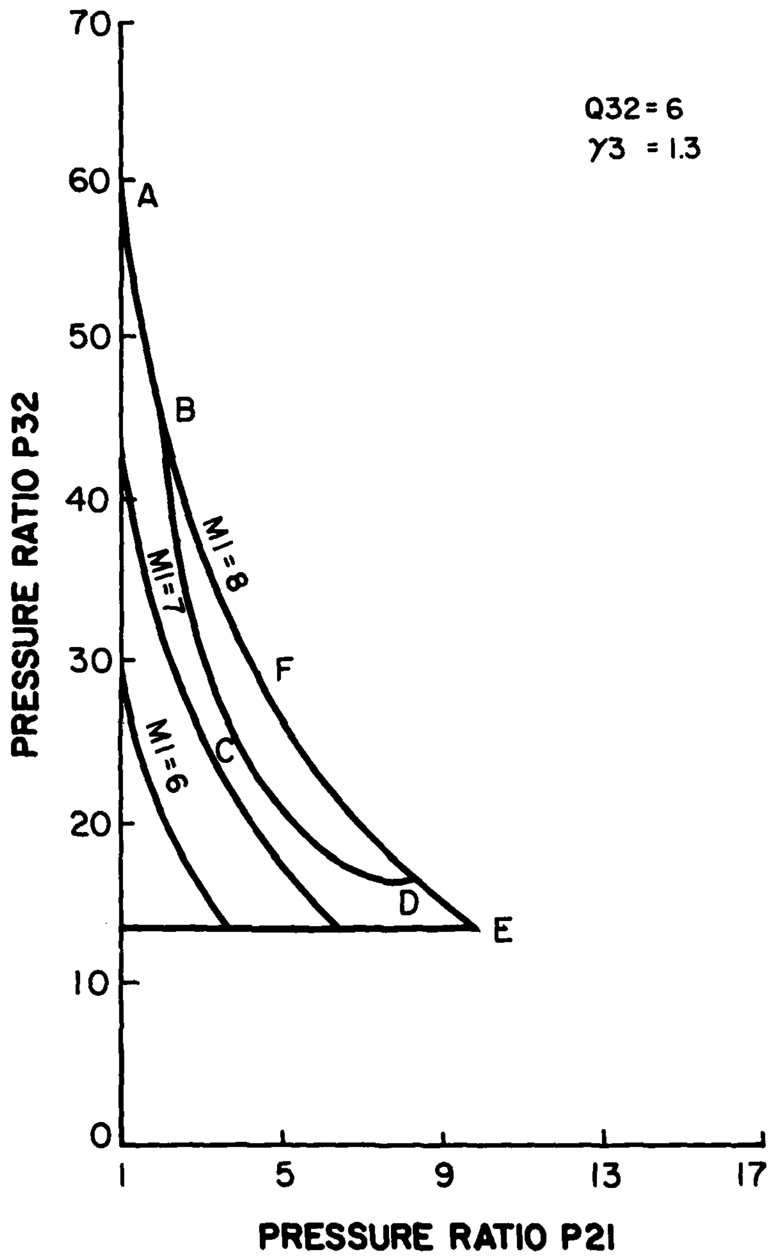

FIG. 11(b). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P_{21}, P_{32} PLANE FOR DIFFERENT VALUES OF THE ONCOMING FLOW MACH NUMBER M_1 (AREAS UNDER THE CORRESPONDING CURVES).

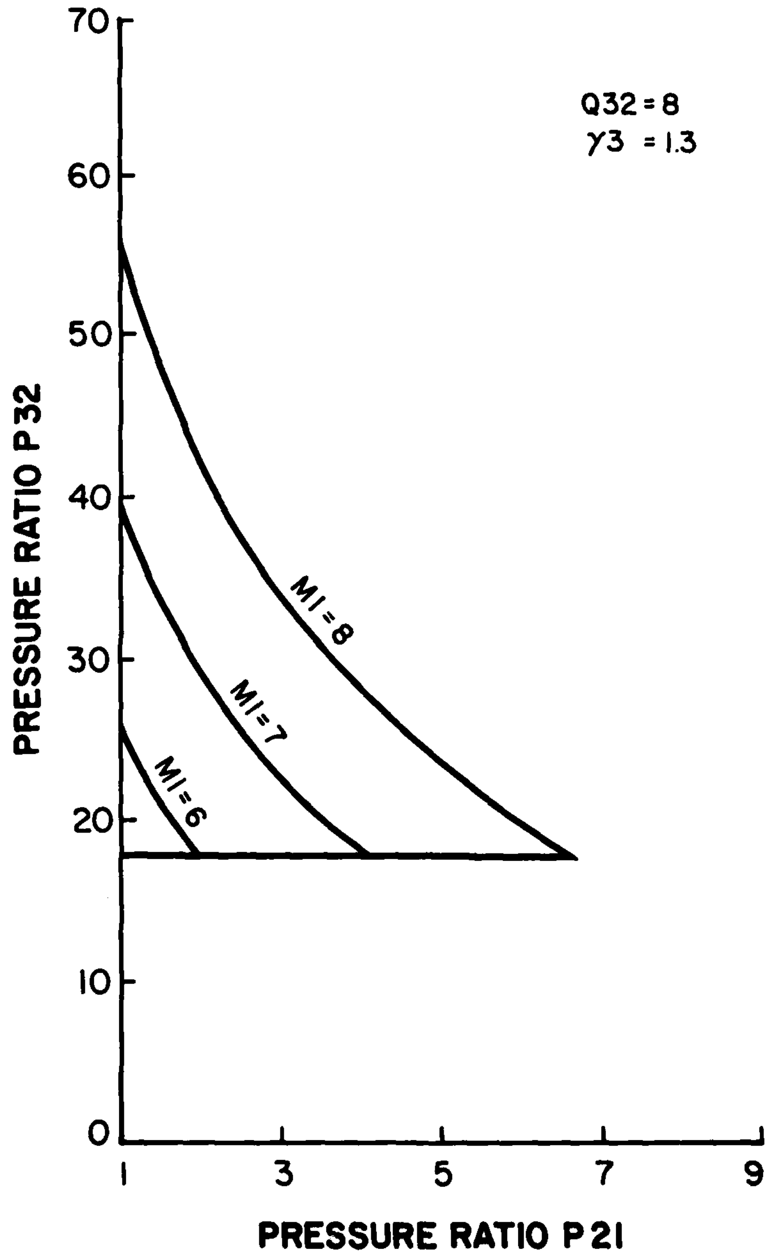

FIG. 11(c). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P_{21}, P_{32} PLANE FOR DIFFERENT VALUES OF THE ONCOMING FLOW MACH NUMBER M_1 (AREAS UNDER THE CORRESPONDING CURVES).

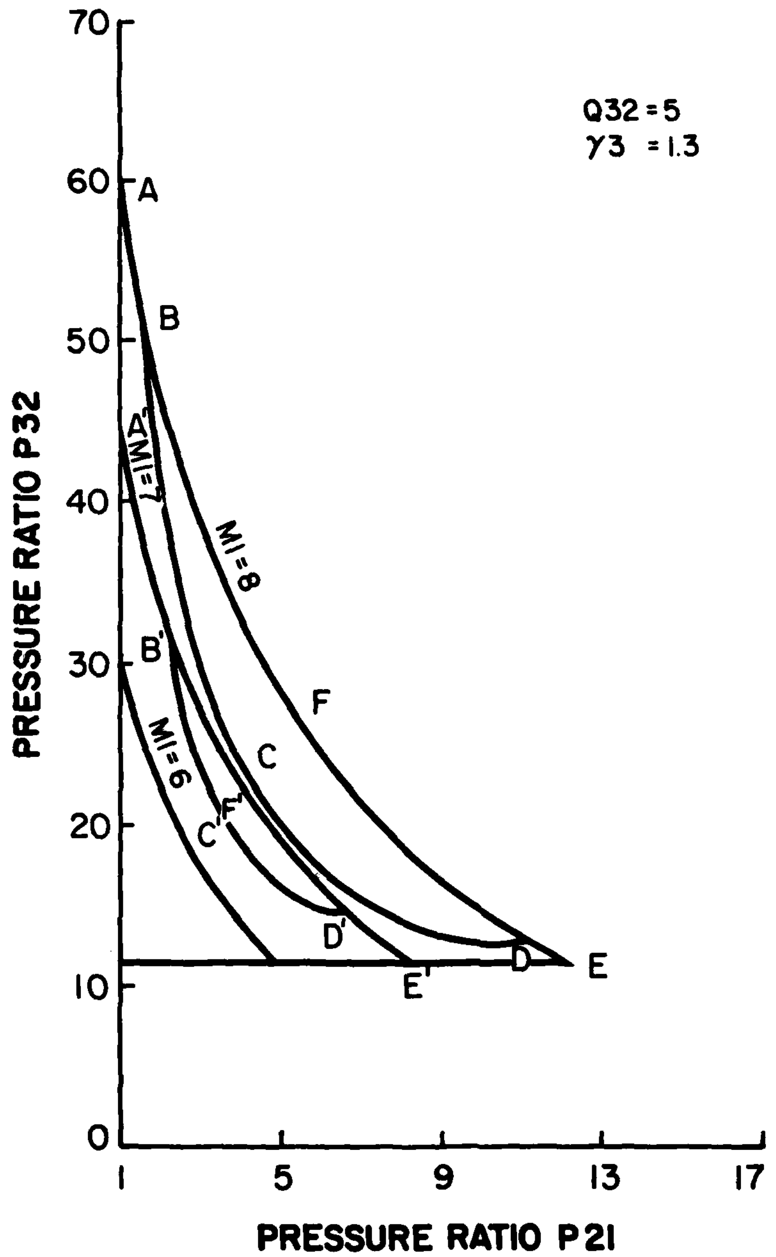

FIG. 11(d). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P21, P32 PLANE FOR DIFFERENT VALUES OF THE ONCOMING FLOW MACH NUMBER M_1 (AREAS UNDER THE CORRESPONDING CURVES).

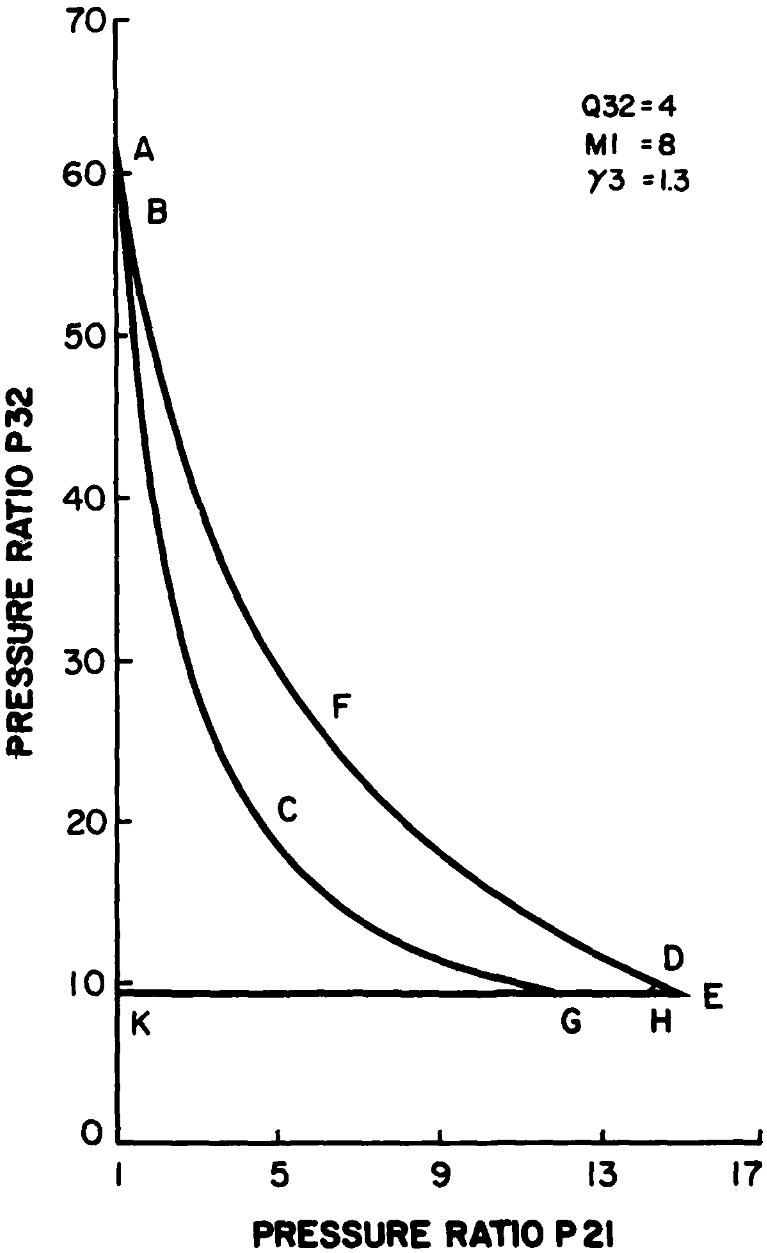

FIG. 11(e). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P_{21}, P_{32} PLANE (AREAS UNDER THE CORRESPONDING CURVES).

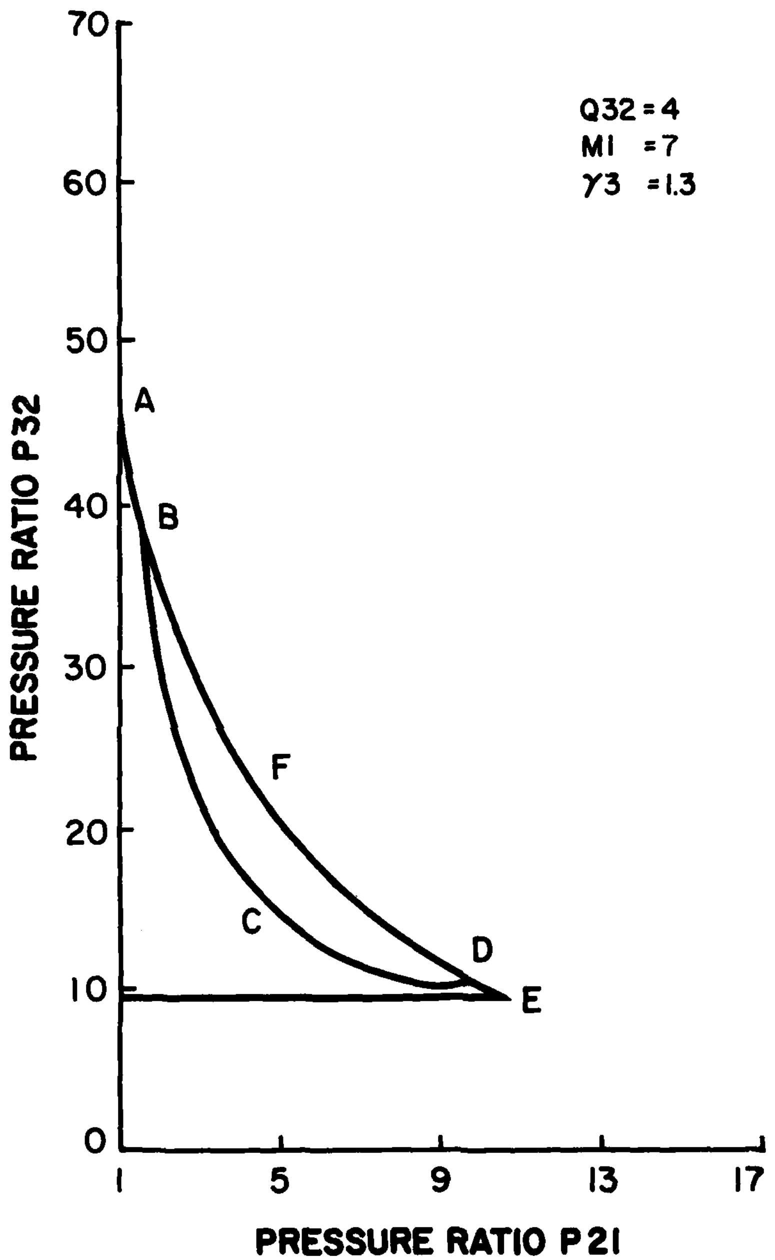

FIG. 11(f). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P_{21}, P_{32} PLANE (AREAS UNDER THE CORRESPONDING CURVES).

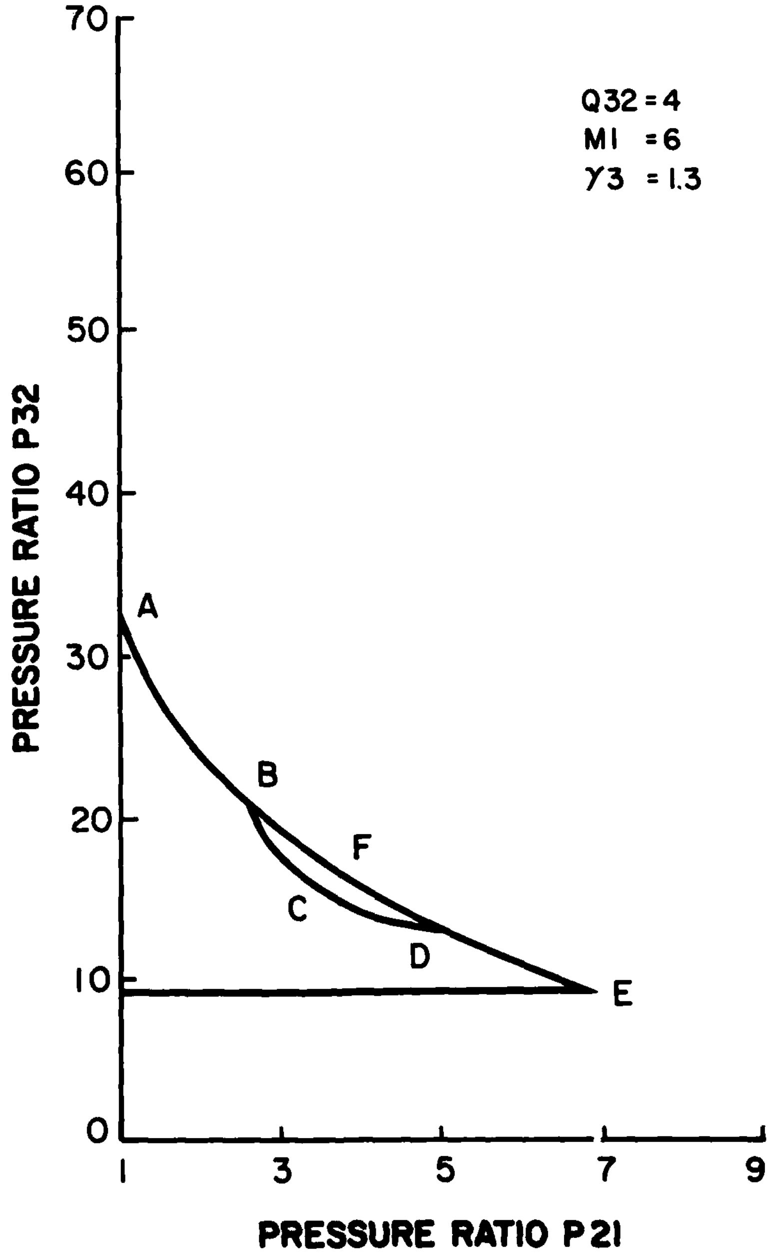

FIG. 11(g). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P_{21}, P_{32} PLANE (AREAS UNDER THE CORRESPONDING CURVES).

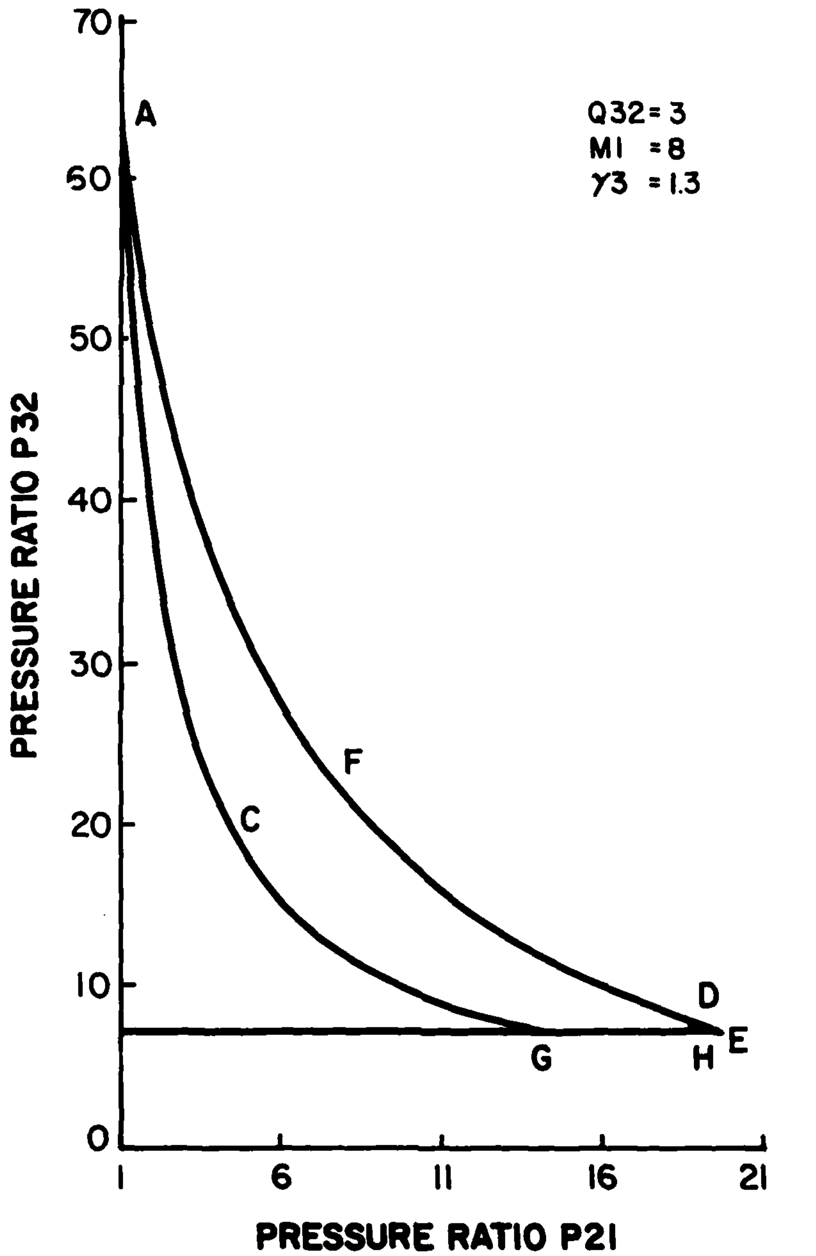

FIG. 11(h). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P_{21}, P_{32} PLANE (AREAS UNDER THE CORRESPONDING CURVES).

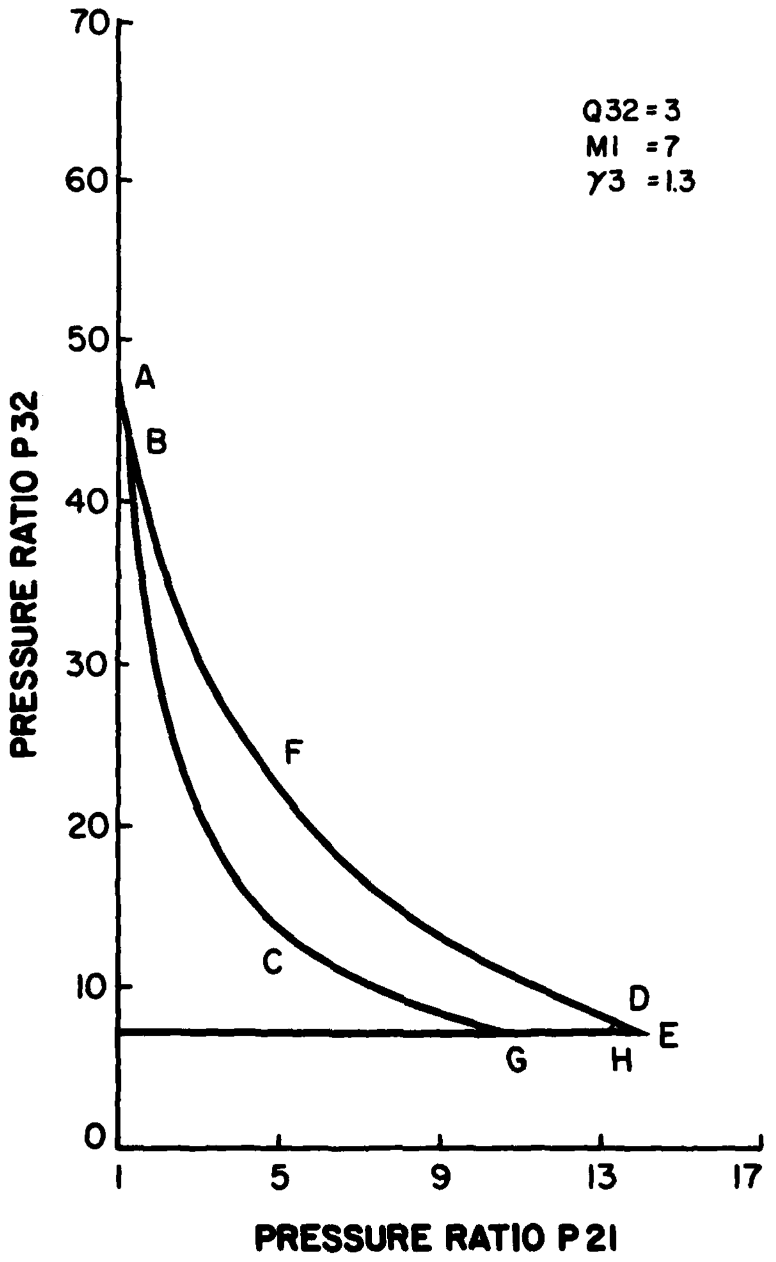

FIG. 11(i). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P_{21}, P_{32} PLANE (AREAS UNDER THE CORRESPONDING CURVES).

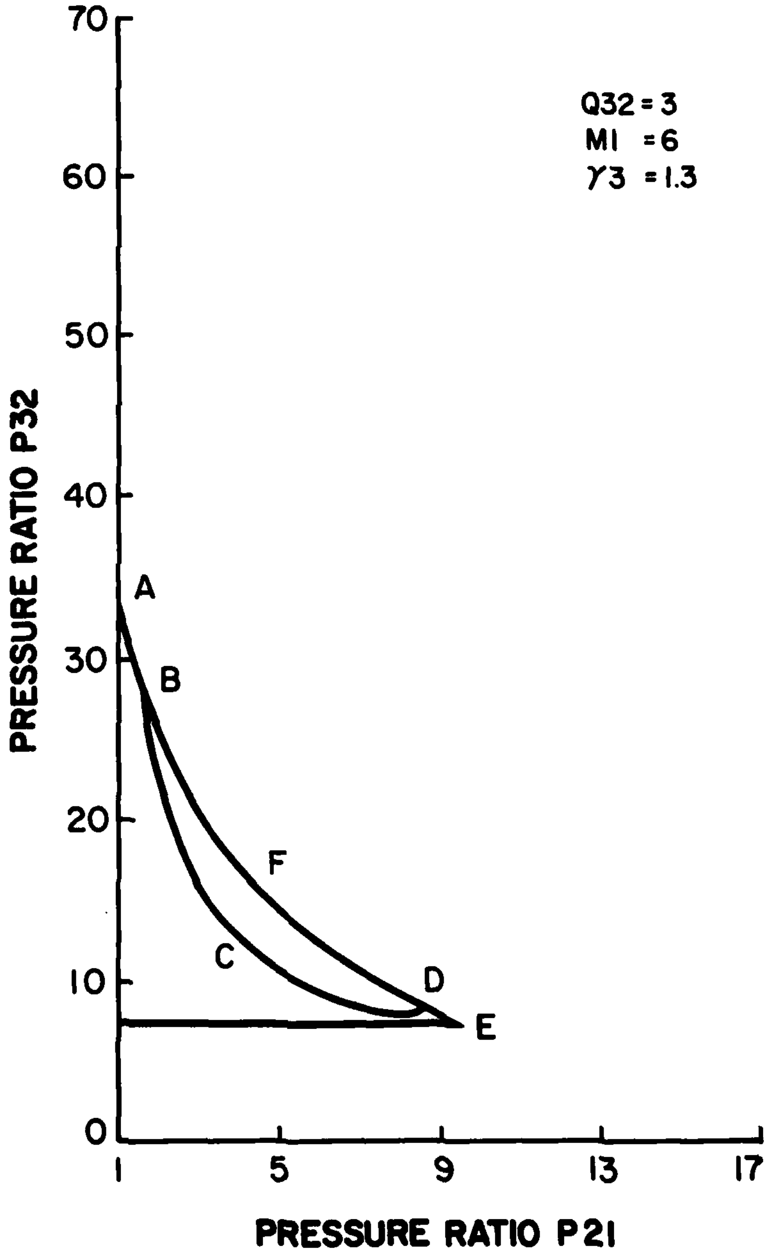

FIG. 11(j). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P_{21}, P_{32} PLANE (AREAS UNDER THE CORRESPONDING CURVES).

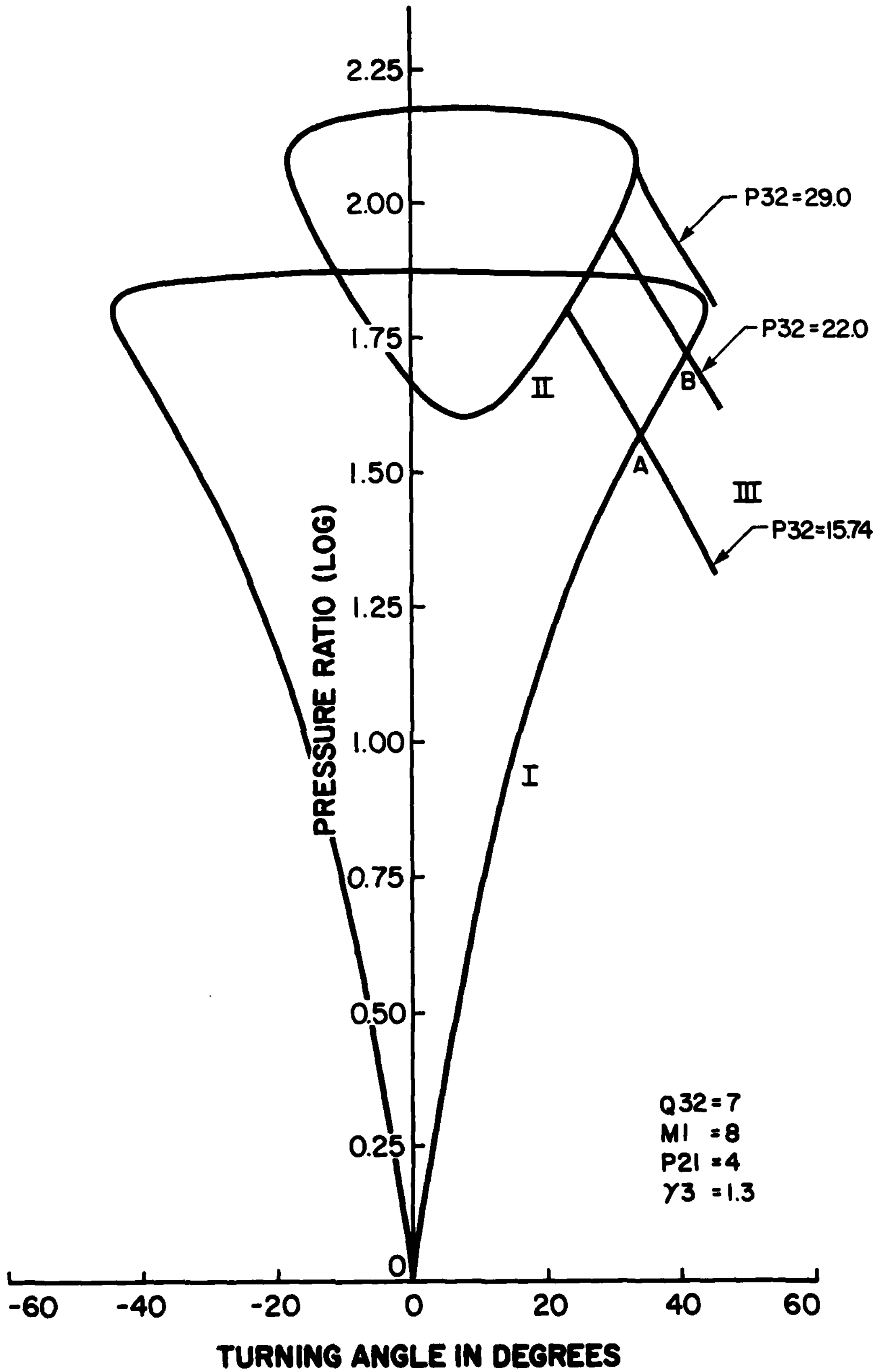

FIG. 12. ILLUSTRATION OF THE UPPER LIMIT OF P32 BEING LOWER THAN P_{32_S}.

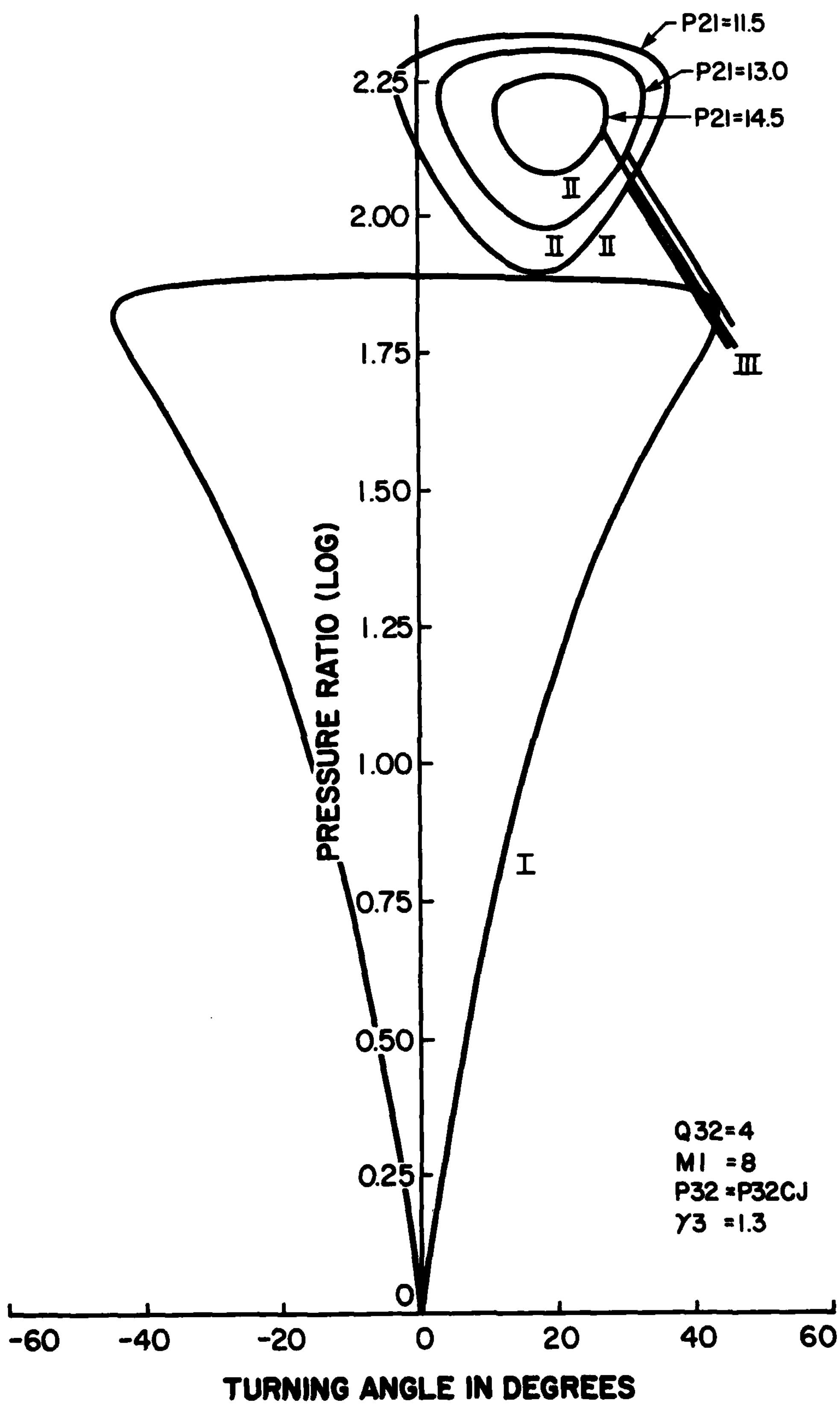

FIG. 13. ILLUSTRATION OF THE DISCONTINUITY OF THE INTERVAL OF P_{21} BECAUSE OF ABSENCE OF INTERSECTION BETWEEN THE EPICYCLOID OF THE REFLECTED RAREFACTION WAVE AND THE TRANSMITTED SHOCK POLAR.

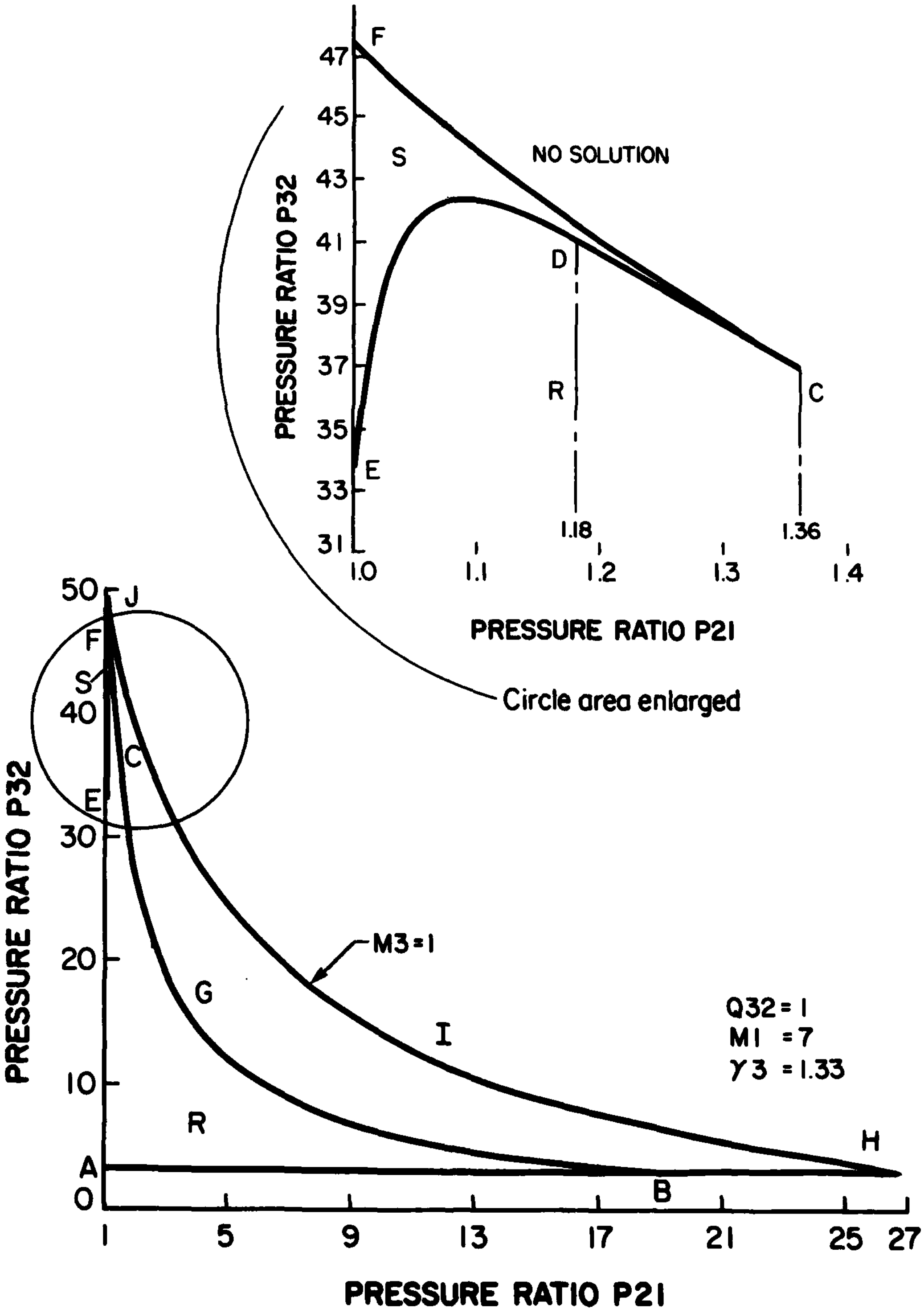

FIG. 14. DOMAINS OF EXISTENCE OF VARIOUS INTERACTION CONFIGURATIONS. S-WITH A REFLECTED SHOCK WAVE; R-WITH A REFLECTED RAREFACTION WAVE.

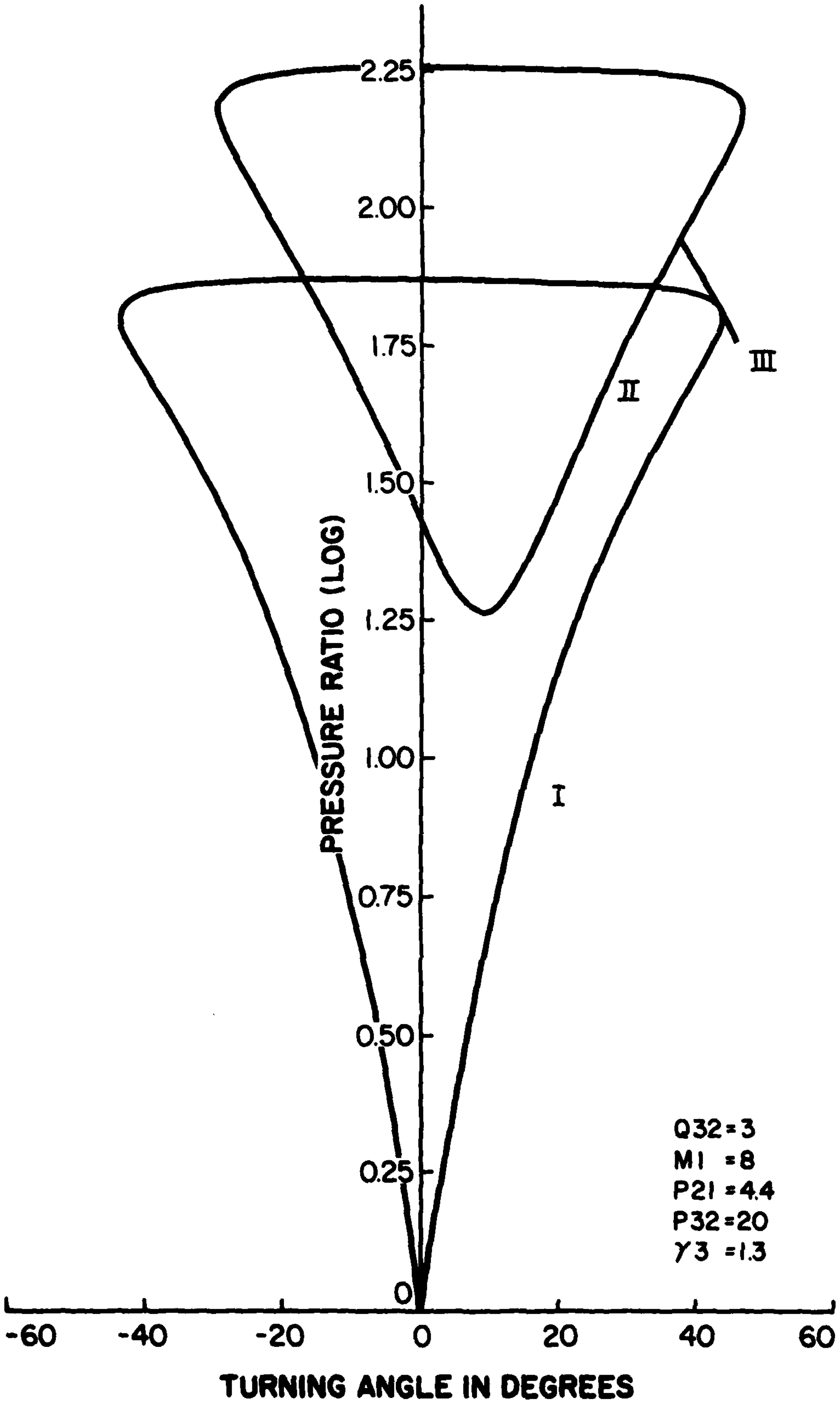

FIG. 15. INTERACTION BETWEEN DETONATION WAVE AND SHOCK WAVE WITH TRANSMITTED SHOCK WAVE ON THE STRONG BRANCH.

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82